



## Experimental Demonstration of Memory-Enhanced Quantum Communication

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# Experimental demonstration of memory-enhanced quantum communication

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The ability to communicate quantum information over long distances is of central impor-11 tance in quantum science and engineering<sup>1</sup>. While some applications of quantum com-12 munication such as secure quantum key distribution (OKD)<sup>2,3</sup> are already being success-13 fully deployed<sup>4-7</sup>, their range is currently limited by photon losses and cannot be extended 14 using straightforward measure-and-repeat strategies without compromising unconditional 15 security<sup>8</sup>. Alternatively, quantum repeaters<sup>9</sup>, which utilize intermediate quantum memory 16 nodes and error correction techniques, can extend the range of quantum channels. However, 17 their implementation remains an outstanding challenge<sup>10-16</sup>, requiring a combination of ef-18 ficient and high-fidelity quantum memories, gate operations, and measurements. Here we 19 use a single solid-state spin memory integrated in a nanophotonic diamond resonator<sup>17-19</sup> to 20

implement asynchronous photonic Bell-state measurements, a key component of quantum
 repeaters. In a proof-of-principle experiment, we demonstrate high-fidelity operation that
 effectively enables quantum communication at a rate that surpasses the ideal loss-equivalent
 direct-transmission method while operating at megahertz clock speeds. These results represent a significant step towards practical quantum repeaters and large-scale quantum networks<sup>2, 20</sup>.

Efficient, long-lived quantum memory nodes are expected to play an essential role in extend-26 ing the range of quantum communication<sup>9</sup>, as they enable asynchronous quantum logic operations, 27 such as Bell-state measurements (BSM), between optical photons. Such an asynchronous BSM is 28 central to many quantum communication protocols, including the realization of scalable quantum 29 repeaters9 with multiple intermediate nodes. Its elementary operation can be understood by con-30 sidering a specific implementation of quantum cryptography<sup>21,22</sup> illustrated in Fig. 1a. Here two 31 remote communicating parties, Alice and Bob, try to agree on a key that is secure against potential 32 eavesdroppers. They each send a randomly chosen photonic qubit  $\{|\pm x\rangle, |\pm y\rangle\}$  encoded in one 33 of two conjugate bases (X or Y) across a lossy channel to an untrusted central node (Charlie), 34 who performs a BSM and reports the result over an authenticated public channel. After a number 35 of iterations, Alice and Bob publicly reveal their choice of bases to obtain a correlated bit string 36 (sifted key) from the cases when they used a compatible basis. A potentially secure key can sub-37 sequently be distilled provided the BSM error rate is low enough. While a photonic BSM can be 38 implemented with linear optics and single photon detectors, in this "direct-transmission" approach, 39 the BSM is only successful when photons from Alice and Bob arrive simultaneously. Thus, when 40 Alice and Bob are separated by a lossy fiber with a total transmission probability  $p_{A\to B} \ll 1$ , Char-41

lie measures photon coincidences with probability also limited by  $p_{A \rightarrow B}$ , leading to a fundamental 42 bound<sup>8</sup> on the maximum possible distilled key rate of  $R_{\text{max}} = p_{A \to B}/2$  bits per channel use for an 43 unbiased basis choice<sup>4</sup>. While linear optical techniques to circumvent this bound are now being 44 actively explored<sup>23</sup>, they offer only limited improvement and cannot be scaled beyond a single 45 intermediate node. Alternatively, this bound can be surpassed using a quantum memory node at 46 Charlie's location. In this approach, illustrated in Fig. 1b, the state of Alice's photon is stored in 47 the heralded memory while awaiting receipt of Bob's photon over the lossy channel. Once the 48 second photon arrives, a BSM between Alice's and Bob's qubits yields a distilled key rate that for 49 an ideal memory scales as<sup>24</sup>  $R_s \propto \sqrt{p_{A \rightarrow B}}$ , potentially leading to substantial improvement over 50 direct transmission. 51

This Letter describes the operation of a quantum node that enables BSM rates that exceed 52 those of an ideal system based on linear optics. We focus on the demonstration and characterization 53 of the BSM node, leaving the implementation of source-specific technical components of full-scale 54 QKD systems, such as decoy states<sup>25</sup>, basis biasing<sup>26</sup>, a finite key error analysis<sup>27</sup>, and a physical 55 separation of Alice and Bob for future work. Our realization is based on a single silicon-vacancy 56 (SiV) color-center integrated inside a diamond nanophotonic cavity<sup>17–19</sup> (Fig. 2a). Its key figure-57 of-merit, the cooperativity<sup>13</sup> C, describes the ratio of the interaction rate with individual cavity 58 photons compared to all dissipation rates. A low mode volume  $(0.5(\lambda/n)^3)$ , high quality factor 59  $(2 \times 10^4)$ , and nanoscale positioning of SiV centers enable an exceptional  $C = 105 \pm 11$ . Cavity 60 photons at 737 nm are critically coupled to a waveguide and adiabatically transferred into a single-61 mode optical fiber<sup>18</sup> that is routed to superconducting nanowire single-photon detectors, yielding 62

<sup>63</sup> a full system detection efficiency of about 85% (Methods). The device is placed inside a dilution <sup>64</sup> refrigerator, resulting in electronic spin quantum memory<sup>19</sup> time  $T_2 > 0.2 \,\mathrm{ms}$  at temperatures <sup>65</sup> below 300 mK.

The operating principle of the SiV-cavity based spin-photon interface is illustrated in Fig. 2. 66 Spin dependent modulation of the cavity reflection at incident probe frequency  $f_0$  (Fig. 2b) results 67 in the direct observation of electron spin quantum jumps (Fig. 2c, inset), enabling nondestructive 68 single-shot readout of the spin state (Fig. 2c) in 30 µs with fidelity  $F = 0.9998^{+0.0002}_{-0.0003}$ . Coherent 69 control of the SiV spin qubit ( $f_Q \approx 12 \,\mathrm{GHz}$ ) is accomplished using microwave fields delivered via 70 an on-chip gold coplanar waveguide<sup>19</sup>. We utilize both optical readout and microwave control to 71 perform projective feedback-based initialization of the SiV spin into the  $|\downarrow\rangle$  state with a fidelity 72 of  $F = 0.998 \pm 0.001$ . Spin-dependent cavity reflection also enables quantum logic operations 73 between an incoming photonic time-bin qubit, defined by a phase-coherent pair of attenuated laser 74 pulses, and the spin memory<sup>19,28</sup>. We characterize this by using the protocol illustrated in Fig. 2d 75 to generate the spin-photon entangled state  $(|e \uparrow\rangle + |l \downarrow\rangle)/\sqrt{2}$  conditioned on successful reflection 76 of an incoming single photon with overall heralding efficiency  $\eta = 0.423 \pm 0.004$  (Methods). 77 Here,  $|e\rangle$  and  $|l\rangle$  denote the presence of a photon in an early or late time-bin separated by  $\delta t =$ 78 142 ns respectively. We characterize the entangled state by performing measurements in the joint 79 spin-photon ZZ and XX bases (Fig. 2e), implementing local operations on the reflected photonic 80 qubit with a time-delay interferometer (Fig. 2a, dashed box). By lowering the average number of 81 photons  $\langle n \rangle_m$  incident on the device during the SiV memory time, we reduce the possibility that 82 an additional photon reaches the cavity without being subsequently detected, enabling high spin-83

<sup>84</sup> photon gate fidelities for small  $\langle n \rangle_m$  (Fig. 2f). For  $\langle n \rangle_m = 0.002$  we measure a lower bound on the <sup>85</sup> fidelity<sup>19</sup> of the spin-photon entangled state of  $F \ge 0.944 \pm 0.008$ , primarily limited by residual <sup>86</sup> reflections from the  $|\downarrow\rangle$  state.

This spin-photon logic gate can be directly used to herald the storage of an incoming pho-87 tonic qubit by interferometrically measuring the reflected photon in the X basis<sup>19</sup>. To implement 88 a memory-assisted BSM, we extend this protocol to accommodate a total of N photonic qubit 89 time-bins within a single initialization of the memory (Fig. 3a). Each individual time-bin qubit 90 is encoded in the relative amplitudes and phases of a pair of neighboring pulses separated by  $\delta t$ . 91 Detection of a reflected photon heralds the arrival of the photonic qubit formed by the two inter-92 fering pulses without revealing its state<sup>19</sup>. Two such heralding events, combined with subsequent 93 spin-state readout in the X basis, constitute a successful BSM on the incident photons. This can 94 be understood without loss of generality by restricting input photonic states to be encoded in the 95 relative phase  $\phi$  between neighboring pulses with equal amplitude:  $(|e\rangle + e^{i\phi} |l\rangle)/\sqrt{2}$  (Fig. 3b). 96 Detection of the first reflected photon in the X basis teleports its quantum state onto the spin, result-97 ing in the state  $(|\uparrow\rangle + m_1 e^{i\phi_1} |\downarrow\rangle)/\sqrt{2}$ , where  $m_1 = \pm 1$  depending on which detector registers the 98 photon<sup>19</sup>. Detection of a second photon at a later time within the electron spin  $T_2$  results in the spin 99 state  $(|\uparrow\rangle + m_1 m_2 e^{i(\phi_1 + \phi_2)} |\downarrow\rangle)/\sqrt{2}$ . The phase of this spin state depends only on the sum of the 100 incoming phases and the product of their detection outcomes, but not the individual phases them-101 selves. As a result, if the photons were sent with phases that meet the condition  $\phi_1 + \phi_2 \in \{0, \pi\}$ , 102 a final measurement of the spin in the X basis  $(m_3 = \pm 1)$  completes an asynchronous BSM, 103 distinguishing two of the four Bell-states based on the total parity  $m_1m_2m_3 = \pm 1$  (Methods). 104

This approach can be directly applied to generate a correlated bit-string within the protocol 105 illustrated in Fig. 1a. We analyze the system performance by characterizing the overall quantum-bit 106 error rate (QBER)<sup>4,21</sup> for N = 124 photonic qubits per memory initialization. We use several ran-107 dom bit strings of incoming photons from  $\{|\pm x\rangle, |\pm y\rangle\}$  and observe strong correlations between 108 the resulting BSM outcome and the initial combination of input qubits for both bases (Fig. 3c). 109 Using this method, we estimate the average QBER to be  $E = 0.116 \pm 0.002$  for all combinations 110 of random bit strings measured, significantly below the limit of  $E_i = 0.146$ , which could provide 111 security against individual attacks<sup>4</sup> (note that the measured error rate is also well below the min-112 imum average QBER<sup>21</sup> of  $E_{lo} = 0.125$  achievable using a linear optics BSM with weak coherent 113 pulse inputs, see Methods). In our experiment, the QBER is affected by technical imperfections in 114 the preparation of random strings of photonic qubits. We find specific periodic patterns of photonic 115 qubits to be less prone to these effects, resulting in a QBER as low as  $E = 0.097 \pm 0.006$ , which 116 falls within the threshold corresponding to unconditional security<sup>3</sup> of  $E_u = 0.110$  with a confi-117 dence level of 0.986 (Methods). We further verify security by testing the Bell-CHSH inequality<sup>14</sup> 118 using input states from four different bases, each separated by an angle of  $45^{\circ}$  (Methods). We find 119 that the correlations between input photons (Fig. 3d) violate the Bell-CHSH inequality  $S_{\pm} \leq 2$ , 120 observing  $S_{\pm} = 2.21 \pm 0.04$  and  $S_{\pm} = 2.19 \pm 0.04$  for positive and negative BSM parity results 121 respectively. This result demonstrates that this device can be used for quantum communication 122 that is secured by Bell's theorem. 123

Finally, we benchmark the performance of memory-assisted quantum communication. For each experiment, we model an effective channel loss by considering the mean photon number  $\langle n \rangle_p$ 

incident on the device per photonic qubit. Assuming that Alice and Bob emit roughly one photon 126 per qubit, this yields an effective channel transmission probability  $p_{A\to B} = \langle n \rangle_p^2$ , resulting in the 127 maximal distilled key rate  $R_{\text{max}}$  per channel use for the direct transmission approach<sup>21</sup>, given by 128 the red line in Fig. 4. We emphasize that this is a theoretical upper bound for a linear optics 129 based BSM, assuming ideal single-photon sources and detectors and balanced basis choices. The 130 measured sifted key rates of the memory-based device are plotted as open circles in Fig. 4. Due to 131 the high overall heralding efficiency and the large number of photonic qubits per memory time (up 132 to N = 504), the memory-assisted sifted key rate exceeds the capability of a linear-optics based 133 BSM device by a factor of  $78.4 \pm 0.7$  at an effective channel loss of about 88 dB. 134

In practice, errors introduced by the quantum memory node could leak information to the en-135 vironment, reducing the quality and potential security of the sifted key<sup>3</sup>. A shorter secure key can 136 be recovered from a sifted key with finite QBER using classical error correction and privacy am-137 plification techniques. The fraction of distilled bits  $r_s$  that can be secure against individual attacks 138 rapidly diminishes<sup>4</sup> as the QBER approaches  $E_i = 0.147$ . For each value of the effective channel 139 loss, we estimate the QBER and use it to compute  $r_s$ , enabling extraction of distilled key rates  $R_s$ , 140 plotted in black in Fig. 4. Even after error-correction, we find that the memory-assisted distilled 141 key rate outperforms the ideal limit for the corresponding direct-transmission implementation by a 142 factor of up to  $R_{\rm S}/R_{\rm max} = 4.1 \pm 0.5$  ( $\pm 0.1$  systematic uncertainty, for N = 124). We further find 143 that this rate also exceeds the fundamental bound on repeaterless communication<sup>8</sup>  $R_{\rm S} \leq 1.44 p_{\rm A \rightarrow B}$ 144 with a statistical confidence level of 99.2% ( $^{+0.2\%}_{-0.3\%}$  systematic uncertainty, see Methods). Despite 145 experimental overhead time associated with operating the device ( $T_R$  in Fig. 1b), the performance 146

of the memory-assisted BSM node (for N = 248) is competitive with an ideal unassisted system running at a 4 MHz average clock rate (Methods).

These experiments demonstrate a form of quantum advantage allowed by memory-based 149 communication nodes and represent a crucial step towards realizing functional quantum repeaters. 150 Several important technical improvements will be necessary to apply this advance for practical 151 long-distance quantum communication. First, this protocol must be implemented using truly inde-152 pendent, distant communicating parties. Additionally, frequency conversion from telecommunica-153 tions wavelengths to  $737 \,\mathrm{nm}$ , as well as low-loss optical elements used for routing photons to and 154 from the memory node, will need to be incorporated. Finally, rapid generation of provably secure 155 keys will require implementation of decoy-state protocols<sup>25</sup>, biased bases<sup>26</sup>, and finite-key error 156 analyses<sup>27</sup>, all compatible with the present approach. With these improvements, our approach is 157 well-suited for deployment in real-world settings. It does not require phase stabilization of long-158 distance links and operates efficiently in the relevant regime of  $p_{A\to B} \approx 70 \,\mathrm{dB}$ , corresponding to 159 about 350 km of telecommunications fiber. Additionally, a single device can be used at the center 160 of a star network topology<sup>29</sup>, enabling quantum communication between several parties beyond the 161 metropolitan scale. Furthermore, the present approach can be extended along several directions. 162 The use of long-lived <sup>13</sup>C nuclear spin qubits could eliminate the need to operate at low total  $\langle n \rangle_m$ 163 and would provide longer storage times, potentially enabling hundred-fold enhancement of BSM 164 success rates<sup>15,19</sup>. Recently implemented strain-tuning capabilities<sup>30</sup> should allow for operation of 165 many quantum nodes at a common network frequency. Unlike linear-optics based alternatives<sup>23</sup>, 166 the approach presented here can be extended to implement the full repeater protocol, enabling a 167

polynomial scaling of the communication rate with distance<sup>9</sup>. Finally, the demonstrated multiphoton gate operations can also be adapted to engineer large cluster-states of entangled photons<sup>31</sup>, which can be utilized for rapid quantum communication<sup>32</sup>. Implementation of these techniques could enable the realization and applications of scalable quantum networks<sup>1</sup> beyond QKD, ranging from non-local quantum metrology<sup>2</sup> to modular quantum computing architectures<sup>20</sup>.



Figure 1: Concept of memory-enhanced quantum communication. a, Quantum communication protocol. Alice and Bob send qubits encoded in photons to a measurement device (Charlie) in between them. Charlie performs a BSM and announces the result. After verifying which rounds Alice and Bob sent qubits in compatible bases, a sifted key is generated. b, Illustration of memoryenhanced protocol. Photons arrive at Charlie from A and B at random times over a lossy channel, and are unlikely to arrive simultaneously (indicated in purple), leading to a low BSM success rate for direct transmission. Despite overhead time  $T_R$  associated with operating a quantum memory (red), a BSM can be performed between photons that arrive at Charlie within memory coherence time  $T_2$ , leading to higher success rates (green). BSM successes and failures are denoted by dark and light shaded windows respectively for both approaches.



Figure 2: Realization of heralded spin-photon gate. a, Schematic of memory-assisted implementation of Charlie's measurement device. Weak pulses derived from a single laser simulate incoming photons from Alice and Bob (purple). Reflected photons (red) are detected in a heralding setup (dashed box). b, Reflection spectrum of memory node, showing spin-dependent device reflectivity. c, Histogram of detected photon numbers during a 30 µs laser pulse, enabling singleshot readout based on a threshold of 7 photons. (Inset) Electron spin quantum jumps under weak illumination. d, Schematic of spin-photon quantum logic operation used to generate and verify spin-photon entangled state. e, Characterization of resulting spin-photon correlations in the ZZ and XX bases. Dashed bars show ideal values. f, Measured spin-photon entanglement fidelity as a function of  $\langle n \rangle_m$ , the average incident photon number during each initialization of the memory.



Figure 3: Asynchronous Bell-state measurements using quantum memory. a, Example sequence with N = 6 photonic qubits sent in a single memory time. Microwave  $\pi$  pulses (green) are interleaved with incoming optical pulses. Photons have fixed amplitude (red) and qubits are defined by the relative phases between subsequent pulses (blue). b, Bloch sphere representation of input photonic time-bin qubits used for characterization. c, Characterization of asynchronous BSM. Conditional probabilities for Alice and Bob to have sent input states (i, j) given a particular parity outcome for input states in the X (top) and Y (bottom) bases. d, Bell test using the CHSH inequality. Conditioned on the BSM outcome, the average correlation between input photons is plotted for each pair of bases used (Methods). Shaded backgrounds denote the expected parity.



Figure 4: Performance of memory-assisted quantum communication. Log-log plot of key rate in bits per channel use versus effective channel transmission  $(p_{A\rightarrow B} = \langle n \rangle_p^2)$ , where  $\langle n \rangle_p$  is the average number of photons incident on the measurement device per photonic qubit). Red line: theoretical maximum for loss-equivalent direct transmission experiment. Green open circles: experimentally measured sifted key rate (green line is the expected rate). To ensure optimal operation of the memory,  $\langle n \rangle_m = \langle n \rangle_p N \approx 0.02$  is kept constant (Methods). From left to right, points correspond to  $N = \{60, 124, 248, 504\}$ . Black filled circles: distilled key rates  $R_S$  using memory device. Vertical error bars are given by the 68% confidence interval and horizontal error bars represent the standard deviation of the systematic power fluctuations.

#### 173 Methods

Experimental setup and device fabrication<sup>18, 30, 33, 34</sup> for millikelvin nanophotonic cavity QED experiments with SiV centers are thoroughly described in a separate publication<sup>35</sup>. Measurements of the cavity QED parameters of the device used in the main text (Extended Data Fig. 1), microwave characterization of the spin qubit (Extended Data Fig. 2), and statistical techniques for estimating QBER are described in detail the Supplementary Methods.

Experimental details. An asynchronous BSM (Fig. 3a) relies on (1) precise timing of the arrival of optical pulses (corresponding to photonic qubits<sup>36,37</sup> from Alice and Bob) with microwave control pulses on the quantum memory and (2) interferometrically stable rotations on reflected time-bin qubits for successful heralding. In order to accomplish (1), all equipment used for generation of microwave and optical fields is synchronized by a single device (National Instriuments HSDIO, Extended Data Fig. 1a) with programming described in Extended Data Table 1-2.

In order to accomplish (2), we use a single, narrow linewidth ( $< 50 \,\mathrm{kHz}$ ) Ti:Sapphire laser 185 (M Squared SolsTiS-2000-PSX-XF, Extended Data Fig. 1b) both for generating photonic qubits 186 and locking the time-delay interferometer (TDI) used to herald their arrival. In the experiment, 187 photonic qubits are reflected from the device, sent into the TDI, and detected on superconducting 188 nanowire single photon detectors (SNSPD, Photon Spot). All detected photons are processed dig-189 itally on a field-programmable gate array (FPGA, Extended Data Fig. 1a), and the arrival times of 190 these heralding signals are recorded on a time-tagger (TT, Extended Data Fig. 1a), and constitute 19 one bit of information of the BSM ( $m_1$  or  $m_2$ ). At the end of the experiment, a 30 µs pulse from 192

the readout path is reflected off the device, and photons are counted in order to determine the spin state  $(m_3)$  depending on the threshold shown in Fig. 2c.

To minimize thermal drift of the TDI, it is mounted to a thermally weighted aluminum bread-195 board, placed in a polyure thane foam-lined and sand filled briefcase, and secured with glue to 196 ensure passive stability on the minute timescale. We halt the experiment and actively lock the in-197 terferometer to the sensitive Y-quadrature every  $\sim 200 \,\mathrm{ms}$  by changing the length of the roughly 198  $28 \,\mathrm{m}$  long (142 ns) delay line with a cylindrical piezo. In order to use the TDI for X-measurements 199 of the reflected qubits, we apply a frequency shift of 1.8 MHz using the qubit AOM, which is 1/4200 of the free-spectral range of the TDI. Since the nanophotonic cavity, the TDI, and the SNSPDs are 201 all polarization sensitive, we use various fiber-based polarization controllers (Extended Data Fig. 202 1b). All fibers in the network are covered with aluminum foil to prevent thermal polarization drifts. 203 This results in an interference visibility of the TDI of > 99% that is stable for several days without 204 any intervention with lab temperature and humidity variations of  $\pm 1^{\circ}$  C and  $\pm 5\%$  respectively. 205

In order to achieve high-fidelity operations we have to ensure that the laser frequency (which 206 is not locked) is resonant with the SiV frequency  $f_0$  (which is subject to the spectral diffusion<sup>35</sup>). 207 To do that we implement a so-called preselection procedure, described in Extended Data Table 208 1-2 and Extended Data Fig. 1a. First, the SiV spin state is initialized by performing a projective 209 measurement and applying microwave feedback. During each projective readout, the reflected 210 counts are compared with two thresholds: a "readout" threshold of 7 photons (used only to record 21  $m_3$ ), and a "status" threshold of 3 photons. The status trigger is used to prevent the experiment 212 from running in cases when the laser is no longer on resonance with  $f_0$ , or if the SiV has ionized to 213

an optically inactive charge state. The duty cycle of the status trigger is externally monitored and is used to temporarily abort the experiment and run an automated re-lock procedure that locates and sets the laser to the new frequency  $f_0$ , reinitalizing the SiV charge state with a 520 nm laser pulse if necessary. This protocol enables fully automated operation at high fidelities (low QBER) for several days without human intervention.

Fiber network. The schematic of the fiber-network used to deliver optical pulses to and collect 219 reflected photons from the nanophotonic memory device is shown in Extended Data Fig. 1b. Pho-220 tons are routed through the lossy (1%) port of a 99:1 fiber beamsplitter (FBS) to the nanophotonic 221 device. We note that for practical implementation of memory-assisted quantum communication, 222 an efficient optical switch or circulator should be used instead. In this experiment, since we focus 223 on benchmarking the performance of the memory device itself, the loss introduced by this beam-224 splitter is incorporated into the estimated channel loss. Reflected photons are collected and routed 225 back through the efficient (99%) port of the FBS and are sent to the TDI in the heralding setup. 226

The outputs of the TDI are sent back into the dilution refrigerator and directly coupled to SNSPDs (PhotonSpot), which are mounted at the 1K stage and are coated with dielectrics to optimize detection efficiency exactly at 737 nm. We estimate all losses that reduce the heralding efficiency  $\eta$  by two independent calibration methods. These rely on three calibrated photodetectors shown in Extended Data Fig. 1b (M1, M2, MC) and are described in detail in the Supplementary Methods, yielding consistent values of  $\eta_1 = 0.425 \pm 0.008$  and  $\eta_2 = 0.422 \pm 0.005$ . This corresponds to a collection efficiency of reflected photons of  $\approx 85\%$ . For values cited in the main text and data points presented in the figures, we use an average value of the heralding efficiency inferred from the two calibration techniques:  $\eta = 0.423 \pm 0.004$ . The residual uncertainty in the heralding efficiency results in a systematic uncertainty, which is explicitly mentioned in the main text where appropriate. We note that this heralding efficiency is consistent with the scaling of spin decoherence with the number of photons at the cavity  $\langle n \rangle_m$ . An example of this effect is shown in the red point in Extended Data Fig. 3e.

**Theoretical description of asynchronous Bell state measurement.** Due to the critical coupling 240 of the nanocavity, the memory node only reflects photons when the SiV spin is in the state  $|\uparrow\rangle$ . 241 The resulting correlations between the spin and the reflected photons can still be used to realize 242 a BSM between two asynchronously arriving photonic time-bin qubits using an adaptation of the 243 well known proposal of Duan and Kimble<sup>28</sup> for entangling a pair of photons incident on an atom-244 cavity system. As a result of the critical coupling, we only have access to two of the four Bell 245 states at any time, with the inaccessible Bell states corresponding to photons being transmitted 246 through the cavity (and thus lost from the detection path). Depending on whether there was an 247 even or odd number of  $\pi$ -pulses on the spin between the arrival of the two heralded photons, we 248 distinguish either the  $\{|\Phi_{\pm}\rangle\}$  or  $\{|\Psi_{\pm}\rangle\}$  states (defined below). For the sake of simplicity, we first 249 describe the BSM for the case when the early time bin of Alice's and Bob's qubits both arrive after 250 an even number of microwave  $\pi$  pulses after its initialization. Thereafter we generalize this result 251 and describe the practical consequences for the quantum communication protocol. 252

The sequence begins with a  $\pi/2$  microwave pulse, preparing the spin in the state  $|\psi_i\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$ . In the absence of a photon at the device, the subsequent microwave  $\pi$ -pulses,

which follow an XY8-N type pattern, decouple the spin from the environment and at the end of the sequence should preserve the spin state  $|\psi_i\rangle$ . However, reflection of Alice's photonic qubit  $|A\rangle = (|e\rangle + e^{i\phi_1} |l\rangle)/\sqrt{2}$  from the device results in the entangled spin-photon state  $|\psi_A\rangle = (|\uparrow e\rangle + e^{i\phi_1} |\downarrow l\rangle)/\sqrt{2}$ . The full system is in the state

$$|\psi_A\rangle = \frac{|+x\rangle \left(|\uparrow\rangle + e^{i\phi_1} |\downarrow\rangle\right) + |-x\rangle \left(|\uparrow\rangle - e^{i\phi_1} |\downarrow\rangle\right)}{2}.$$
(1)

Regardless of the input photon state, there is equal probability to measure the reflected photon to be  $|\pm x\rangle$ . Thus, measuring the photon in X basis (through the TDI) does not reveal the initial photon state. After this measurement, the initial state of the photon  $|A\rangle$  is teleported onto the spin:  $|\psi_{m_1}\rangle = (|\uparrow\rangle + m_1 e^{i\phi_1} |\downarrow\rangle)\sqrt{2}$ , where  $m_1 = \pm 1$  denotes the detection outcome of the TDI<sup>19,38</sup>. The quantum state of Alice's photon is now stored in the spin state, which is preserved by the dynamical decoupling sequence.

Reflection of the second photon  $|B\rangle = (|e\rangle + e^{i\phi_2} |l\rangle)\sqrt{2}$  from Bob results in the spin-photon state  $|\psi_{m_1,B}\rangle = (|\uparrow e\rangle + m_1 e^{i(\phi_1 + \phi_2)} |\downarrow l\rangle)/\sqrt{2}$ . This state now has a phase that depends on the initial states of both photons, enabling the photon-photon BSM measurements described below. Rewriting Bob's reflected photon in the X basis, the full system is in the state

$$\left|\psi_{m_{1},B}\right\rangle = \frac{\left|+x\right\rangle\left(\left|\uparrow\right\rangle + m_{1}e^{i\left(\phi_{1}+\phi_{2}\right)}\left|\downarrow\right\rangle\right) + \left|-x\right\rangle\left(\left|\uparrow\right\rangle - m_{1}e^{i\left(\phi_{1}+\phi_{2}\right)}\left|\downarrow\right\rangle\right)}{2}.$$
(2)

The second measurement result  $m_2$  once again contains no information about the initial state  $|B\rangle$ , yet heralds the final spin state  $|\psi_{m_1,m_2}\rangle = (|\uparrow\rangle + m_1m_2e^{i(\phi_1+\phi_2)}|\downarrow\rangle)$  as described in the main text. When this state lies along the X axis of the Bloch sphere  $(\phi_1 + \phi_2 = \{0, \pi\})$ , the final result of the X basis measurement on the spin state  $m_3$  has a deterministic outcome, dictated by all values of the parameters  $\{\phi_1, \phi_2\}$  (known only to Alice and Bob) and  $\{m_1, m_2\}$  (which are known to Charlie, but are completely random). Conversely, all information available to Charlie  $\{m_1, m_2, m_3\}$  only contains information on the correlation between the photonic qubits, not on their individual states. The resulting truth table for different input states is given in Extended Data Table 3. For all input states, there is equal probability of measuring  $\pm 1$  for each individual measurement  $m_i$ . However, the overall parity of the three measurements  $m_1m_2m_3$  depends on whether or not the input photons were the same, or opposite, for inputs  $|A\rangle$ ,  $|B\rangle \in |\pm x\rangle$  or  $|\pm y\rangle$ .

We now address the fact that the BSM distinguishes either between  $\{|\Phi_{\pm}\rangle\}$  or  $\{|\Psi_{\pm}\rangle\}$  if there was an even or odd number of microwave  $\pi$  pulses between incoming photons respectively. This effect arises because each  $\pi$  pulse in the dynamical decoupling sequence toggles an effective frame change:  $Y \leftrightarrow -Y$ . The impact on this frame change on the BSM can be seen by writing the pairs of Bell states  $(|\Phi_{\pm}\rangle = (|ee\rangle \pm |ll\rangle)/\sqrt{2}$  and  $|\Psi_{\pm}\rangle = (|el\rangle \pm |le\rangle)/\sqrt{2}$ ) in the X and Y bases, where we have

$$\Phi_{\pm}\rangle^{(X)} = (|+x\rangle |\pm x\rangle + |\mp x\rangle |-x\rangle)/\sqrt{2}$$
(3)

$$|\Phi_{\pm}\rangle^{(Y)} = (|+y\rangle |\mp y\rangle + |\pm y\rangle |-y\rangle)/\sqrt{2}$$
(4)

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$$\left|\Psi_{\pm}\right\rangle^{(X)} = \left(\left|\pm x\right\rangle \left|\pm x\right\rangle - \left|\mp x\right\rangle \left|-x\right\rangle\right)/\sqrt{2} \tag{5}$$

$$|\Psi_{\pm}\rangle^{(Y)} = i(|\pm y\rangle |\pm y\rangle - |\mp y\rangle |-y\rangle)/\sqrt{2}$$
(6)

For X basis inputs, as seen by Eq. 3 and 5, switching between  $\{|\Phi_{\pm}\rangle\}$  and  $\{|\Psi_{\pm}\rangle\}$  measurements does not affect the inferred correlation between input photons. For Y basis inputs however, this does result in an effective bit flip in the correlation outcome (see Eq. 4 and 6). In practice, Alice and Bob can keep track of each Y photon sent and apply a bit flip accordingly, as long as they have
the appropriate timing information about MW pulses applied by Charlie. If Charlie does not give
them the appropriate information, this will result in an increased QBER which can be detected.

As an additional remark, this scheme also works for pairs of photons that are not both in the X or Y basis but still satisfy the condition  $\phi_1 + \phi_2 = 0$ . For example,  $|a\rangle$  and  $|b\rangle$  from Fig. 3b satisfy this condition. In this case, adequate correlations can still be inferred about the input photons, although they were sent in different bases.

Finally, we would like to note that this asynchronous scheme for performing a BSM between 299 two pulses has an important advantage over the synchronous, linear-optical implementation. In the 300 case where Alice and Bob use attenuated laser pulses to encode photonic qubits, which is by far 301 the most technologically simple implementation, there is an inherent QBER of 25% for photons 302 sent in the X and Y bases. This is because the linear-optical implementation relies on the pulses to 303 overlap on a beamsplitter and interfere via the Hong-ou-Mandel effect, which has a finite visibility 304 of 50% for coherent pulses<sup>21</sup>. Intuitively, this finite error arises from a fundamental inability to 305 distinguish between detection outcomes where two individual single-photons arrived from Alice 306 and Bob versus a two-photon component from either Alice or Bob in the synchronous scheme. In 307 the asynchronous scheme, since pulses do not arrive at the same time from Alice and Bob, this 308 error is mitigated. As a result, for ideal quantum memory operation and sufficiently attenuated 309 laser pulses, the ultimate limit to the QBER is zero. 310

Test of Bell-CHSH inequality. In order to perform a test of the Bell-CHSH inequality<sup>39</sup>, we send input photons equally distributed from all states  $\{|\pm x\rangle, |\pm y\rangle, |\pm a\rangle, |\pm b\rangle\}$  (Fig. 3b). We select for cases where two heralding events arise from input photons  $\{A, B\} = \pm 1$  that are either 45° or 135° apart from one another. Conditioned on the parity outcome of the BSM (±1), the Bell-CHSH inequality bounds the correlations between input photons as

$$S_{\pm} = |\langle A \cdot B \rangle_{xa} - \langle A \cdot B \rangle_{xb} - \langle A \cdot B \rangle_{ya} - \langle A \cdot B \rangle_{yb}| \le 2, \tag{7}$$

where the subscripts denote the bases the photons were sent in. The values of each individual term in Eq. 7, denoted as "input correlations," are plotted in Fig. 3d for positive and negative parity outcomes.

Optimal parameters for asynchronous Bell state measurements. We minimize the experimentally extracted QBER for the asynchronous BSM to optimize the performance of the memory node. The first major factor contributing to QBER is the scattering of a third photon that is not detected, due to the finite heralding efficiency  $\eta = 0.423 \pm 0.04$ . This is shown in Fig. 2f, where the fidelity of the spin-photon entangled state diminishes for  $\langle n \rangle_m \gtrsim 0.02$ . At the same time, we would like to work at the maximum possible  $\langle n \rangle_m$  in order to maximize the data rate to get enough statistics to extract QBER (and in the quantum communication setting, efficiently generate a key).

To increase the key generation rate per channel use, one can also fit many photonic qubits within each initialization of the memory. In practice, there are 2 physical constraints: (1) the bandwidth of the SiV-photon interface and (2) the coherence time of the memory. We find that one can satisfy (1) at a bandwidth of roughly 50 MHz with no measurable infidelity. For shorter optical <sup>330</sup> pulses (< 10 ns), the spin-photon gate fidelity is reduced. In principle, the SiV-photon bandwidth <sup>331</sup> can be increased by reducing the atom-cavity detuning (here  $\sim 60 \text{ GHz}$ ) at the expense of having <sup>332</sup> to operate at higher magnetic fields where microwave qubit manipulation is not as convenient<sup>35</sup>.

Even with just an XY8-1 decoupling sequence (number of  $\pi$  pulses  $N_{\pi} = 8$ ), the coherence 333 time of the SiV is longer than  $200 \,\mu s$  (Extended Data Fig. 3c) and can be prolonged to the mil-334 lisecond range with longer pulse sequences<sup>19</sup>. Unfortunately, to satisfy the bandwidth criteria (1) 335 and to drive both hyperfine transitions (Extended Data Fig. 3a), we must use short (32 ns long  $\pi$ 336 pulses), which cause additional decoherence from ohmic heating<sup>35</sup> already at  $N_{\pi} = 64$  (Extended 337 Data Fig. 3e). Due to this we limit the pulse sequences to a maximum  $N_{\pi} = 128$ , and only use up 338 to  $\approx 20 \,\mu s$  of the memory time. One solution would be to switch to superconducting microwave 339 delivery. Alternatively, one can use a larger value of  $\tau$  to allow the device to cool down in between 340 subsequent pulses<sup>35</sup> at the expense of having to stabilize a TDI of larger  $\delta t$ . Working at larger  $\delta t$ 341 also enables temporal multiplexing by fitting multiple time-bin qubits per free-precession interval. 342 In fact, with  $2\tau = 142$  ns, even given constraint (1) and the finite  $\pi$  time, we can already fit up to 343 4 optical pulses per free-precession window, enabling a total number of photonic qubits of up to 344 N = 504 for only  $N_{\pi} = 128$ . 345

In benchmarking the asynchronous BSM for quantum communication, we optimize the parameters  $\langle n \rangle_m$  and N to maximize our enhancement over the direct transmission approach, which is a combination of both increasing N and reducing the QBER, since a large QBER results in a small distilled key fraction  $r_s$ . As described in the main text, the effective loss can be associated with  $\langle n \rangle_p$ , which is the average number of photons per photonic qubit arriving at the device, and is given straightforwardly by  $\langle n \rangle_p = \langle n \rangle_m / N$ . The most straightforward way to sweep the loss is to keep the experimental sequence the same (fixed N) and vary the overall power, which changes  $\langle n \rangle_m$ . The results of such a sweep are shown in Extended Data Fig. 5a, b. For larger  $\langle n \rangle_m$  (corresponding to lower effective channel losses), the errors associated with scattering an additional photon reduce the performance of the memory device.

Due to these considerations, we work at roughly  $\langle n \rangle_m \lesssim 0.02$  for experiments in the main 356 text shown in Fig. 3 and 4, below which the performance does not improve significantly. At this 357 value, we obtain BSM successes at a rate of roughly 0.1 Hz. By fixing  $\langle n \rangle_m$  and increasing N, we 358 maintain a tolerable BSM success rate while increasing the effective channel loss. Eventually, as 359 demonstrated in Extended Data Fig. 5c and in the high-loss data point in Fig. 4, effects associated 360 with microwave heating result in errors that again diminish the performance of the memory node 36 for large N. As such, we conclude that the optimal performance of our node occurs for  $\left\langle n\right\rangle_m \sim$ 362 0.02 and  $N \approx 124$ , corresponding to an effective channel loss of 69 dB between Alice and Bob, 363 which is equivalent to roughly  $350 \,\mathrm{km}$  of telecommunications fiber. 364

We also find that the QBER and thus the performance of the communication link is limited by imperfect preparation of photonic qubits. Photonic qubits are defined by sending arbitrary phase patterns generated by the optical AWG to a phase modulator. For an example of such a pattern, see the blue curve in Fig. 3a. We use an imperfect pulse amplifier with finite bandwidth (0.025 - 700MHz), and find that the DC component of these waveforms can result in error in photonic qubit preparation on the few % level. By using a tailored waveform of phases with smaller (or vanishing) DC component, we can reduce these errors. We run such an experiment during the test of the Bell<sup>372</sup> CHSH inequality. We find that by evaluating BSM correlations from  $|\pm a\rangle$  and  $|\pm b\rangle$  inputs during <sup>373</sup> this measurement, we estimate a QBER of  $0.097 \pm 0.006$ .

Finally, we obtain the effective clock-rate of the communication link by measuring the total 374 number of photonic qubits sent over the course of an entire experiment. In practice, we record 375 the number of channel uses, determined by the number of sync triggers recorded (see Extended 376 Data Fig. 1a) as well as the number of qubits per sync trigger (N). We then divide this number by 377 the total experimental time from start to finish ( $\sim 1-2$  days for most experimental runs), including 378 all experimental downtime used to stabilize the interferometer, readout and initialize the SiV, and 379 compensate for spectral diffusion and ionization. For N = 248, we extract a clock rate of 1.2 MHz. 380 As the distilled key rate in this configuration exceeds the conventional limit of p/2 by a factor of 38  $3.8\pm1.1,$  it is competitive with a standard linear-optics based system operating at  $4.5^{+1.3}_{-1.2}~\mathrm{MHz}$ 382 clock rate. 383

Performance of memory-assisted quantum communication. A single optical link can provide 384 many channels, for example, by making use of different frequency, polarization, or temporal 385 modes. To account for this, when comparing different systems, data rates can be defined on a 386 per-channel-use basis. In a quantum communication setting, full usage of the communication 387 channel between Alice and Bob means that both links from Alice and Bob to Charlie are in use 388 simultaneously. For an asynchronous sequential measurement, typically only half of the channel is 389 used at a time, for example from Alice to Charlie or Bob to Charlie. The other half can in principle 390 be used for a different task when not in use. For example, the unused part of the channel could be 39' routed to a secondary asynchronous BSM device. In our experiment, we can additionally define 392

as a second normalization the rate per channel "occupancy", which accounts for the fact that only half the channel is used at any given time. The rate per channel occupancy is therefore half the rate per full channel use. For comparison, we typically operate at 1.2% channel use and 2.4% channel occupancy.

To characterize the optimal performance of the asynchronous Bell state measurement device, we operate it in the optimal regime determined above (N = 124,  $\langle n \rangle_m \lesssim 0.02$ ). We note that the enhancement in the sifted key rate over direct transmission is given by

$$\frac{R}{R_{\rm max}} = \eta^2 \frac{(N_{\pi} - 1)(N_{\pi} - 2)N_{\rm sub}}{2N_{\pi}}$$
(8)

and is independent of  $\langle n \rangle_m$  for a fixed number of microwave pulses  $N_\pi$  and optical pulses per 400 microwave pulse  $N_{sub}$  and thus fixed  $N = N_{\pi}N_{sub}$ . For low  $\langle n \rangle_m$ , three photon events become 401 negligible and therefore QBER saturates, such that the enhancement in the distilled key rate satu-402 rates as well (Extended Data Fig. 5a). We can therefore combine all data sets with fixed N = 124403 below  $\langle n \rangle_m \lesssim 0.02$  to characterize the average QBER of  $0.116 \pm 0.002$  (Fig. 3c). The key rates 404 cited in the main text relate to a data set in this series ( $\langle n \rangle_m \approx 0.02$ ), with a QBER of  $0.110 \pm 0.004$ . 405 A summary of key rates calculated on a per-channel use and per-channel occupancy basis, as well 406 as comparisons of performance to an ideal linear-optics BSM and the repeaterless bound<sup>8</sup> are given 407 in Extended Data Table 4. 408

Furthermore, we extrapolate the performance of our memory node to include biased input bases from Alice and Bob. This technique enables a reduction of channel uses where Alice and Bob send photons in different bases, but is still compatible with secure key distribution<sup>26</sup>, allowing for enhanced distilled key rates by at most a factor of 2. The extrapolated performance of our node for a bias of 99:1 is also displayed in Extended Data Table 4, as well as comparisons to the relevant bounds. We note that basis biasing does not affect the performance when comparing to the equivalent direct-transmission experiment, which is limited by  $p_{A\to B}/2$  in the unbiased case and  $p_{A\to B}$  in the biased case. However, using biased input bases does make the performance of the memory-assisted approach more competitive with the fixed repeaterless bound<sup>8</sup> of  $1.44p_{A\to B}$ .



**Extended Data Figure 1: Experimental schematic. a,** Control flow of experiment. Opt (MW) AWG is a Tektronix AWG7122B 5 GS/s (Tektronix AWG70001a 50 GS/s) arbitrary waveform generator used to generate photonic qubits (microwave control signals). All signals are recorded on a time-tagger (TT, PicoQuant HydraHarp 400). **b,** Fiber network used to deliver photons to and collect photons from the memory device, including elements for polarization control and diagnostic measurements of coupling efficiencies. **c,** Preparation of optical fields. The desired phase relation between lock and qubit paths is ensured by modulating AOMs using phase-locked RF sources with a precise 1.8 MHz frequency shift between them.



Extended Data Figure 2: Characterization of device cooperativity. a, Cavity reflection spectrum far-detuned (blue) and on resonance (red) with SiV center. Blue solid line is a fit to a Lorentzian, enabling extraction of linewidth  $\kappa = 21.8 \text{ GHz}$ . Red solid line is a fit to a model used to determine the single-photon Rabi frequency  $g = 8.38 \pm 0.05 \text{ GHz}$  and shows the onset of a normal mode splitting. b, Measurement of SiV linewidth far detuned ( $\Delta_c = 248 \text{ GHz}$ ) from cavity resonance. Red solid line is a fit to a Lorentzian, enabling extraction of natural linewidth  $\gamma = 0.123 \text{ GHz}$ .



Extended Data Figure 3: Microwave characterization of spin-coherence properties. a, ODMR spectrum of the qubit transition at ~ 12 GHz split by coupling to a nearby <sup>13</sup>C . b, Rabi oscillations showing  $\pi$  time of 30 ns. A  $\pi$  time of 32 ns is used for experiments in the main text. c, XY8-1 dynamical decoupling signal (unnormalized) as a function of total time *T*, showing coherence lasting on the several hundred µs timescale. d, XY8-8 dynamical decoupling signal (normalized) revealing region of high fidelity at relevant value of  $2\tau = 142$  ns. e, Fidelity of spin state after dynamical decoupling sequence with varying number of  $\pi$  pulses ( $N_{\pi}$ ), blue points. Red point (diamond) is under illumination with  $\langle n \rangle_m = 0.02$ .



Extended Data Figure 4: Measurements on a single time-bin qubit in Z and X bases. a, Example of optical pulses sent for example in the experiment described in Fig. 2d. b, Time trace of detected photons on + detector when pulses shown in (a) are sent directly into the TDI. The first and last peaks correspond to late and early photons taking the long and short paths of the TDI, which enable measurements in the Z basis  $\{|e\rangle, |l\rangle\}$ . The central bin corresponds to the late and early components overlapping and interfering constructively to come out of the + port, equivalent to a measurement of the time bin qubit in the  $|+x\rangle$  state. A detection event in this same timing window on the - detector (not shown) would constitute a  $|-x\rangle$  measurement. In this measurement, the TDI was left unlocked, so we observe no interference in the central window.



Extended Data Figure 5: Performance of memory-device versus of channel loss. a, Enhancement of memory-based approach compared to direct transmission approach, keeping N = 124fixed and varying  $\langle n \rangle_m$  in order to vary the effective channel transmission probability  $p_{A\to B}$ . At high  $p_{A\to B}$  (larger  $\langle n \rangle_m$ ),  $r_s$  approaches 0 due to increased QBER arising from undetected scattering of a third photon. b, (Left) Plot of QBER for same sweep of  $\langle n \rangle_m$  shown in a. (Right) Plot of QBER while sweeping N in order to vary loss. These points correspond to the same data shown in Fig. 4. At lower  $p_{A\to B}$  (larger N), microwave-induced heating-related dephasing leads to increased QBER.

Step	Process	Duration	Proceed to
1	Lock time-delay interferometer	$200\mathrm{ms}$	2
2	Readout SiV	$30\mu s$	If status LOW: 4, else: 3
3	Apply microwave $\pi$ pulse	$32\mathrm{ns}$	2
4	Run main experiment script	$\sim 200\mathrm{ms}$	1

**Extended Data Table 1: High-level experimental sequence**. This sequence is programmed into the HSDIO and uses feedback from the status trigger sent from the FPGA (see Extended Data Fig. 1a). Main experimental sequence is described in Extended Data Table 2. External software is also used to monitor the status trigger. If it is HI for  $\geq 2$  s, the software activates an automatic re-lock procedure which compensates for spectral diffusion and ionization of the SiV center (Methods).

Step	Process	Duration	Proceed to
1	Run sequence in Fig. 3a for a given $N$	$10-20 \ \mu s$	2
2	Readout SiV + report readout to TT	$30\mu s$	If status LOW: 1, else: 3
3	Apply microwave $\pi$ pulse	$32\mathrm{ns}$	4
4	Readout SiV	$30\mu s$	If status LOW: 3, else: 1

Extended Data Table 2: Main experimental sequence for memory-enhanced quantum communication. This script is followed until step 1 is run a total of 4000 times, and then terminates and returns to step 1 of Extended Data Table 1. The longest step is the readout step, which is limited by the fact that we operate at a photon detection rate of  $\sim 1 \text{ MHz}$  to avoid saturation of the SNSPDs.

Alice	Bob	Parity	Bell state
$ +x\rangle$	$ +x\rangle$	+1	$ \Phi_+ angle$
$ +x\rangle$	$ -x\rangle$	-1	$ \Phi_{-} angle$
$ -x\rangle$	$ +x\rangle$	-1	$ \Phi_{-} angle$
$ -x\rangle$	$ -x\rangle$	+1	$ \Phi_+ angle$
$ +y\rangle$	$ +y\rangle$	-1	$ \Phi_{-} angle$
$ +y\rangle$	$ -y\rangle$	+1	$ \Phi_+ angle$
$ -y\rangle$	$ +y\rangle$	+1	$ \Phi_+ angle$
$\left -y\right\rangle$	$ -y\rangle$	-1	$ \Phi_{-} angle$

**Extended Data Table 3: Truth table of asynchronous BSM protocol**, showing the parity (and BSM outcome) for each set of valid input states from Alice and Bob. In the case of Y basis inputs, Alice and Bob adjust the sign of their input state depending on whether it was commensurate with an even or odd numbered free-precession interval, based on timing information provided by Charlie (Methods).

	per channel occupancy	per channel occupancy	per channel use	per channel use
X:Y basis bias	50:50	99:1	50:50	99:1
Distilled key rate $R [10^{-7}]$	$1.19^{+0.14}_{-0.14}$	$2.33^{+0.28}_{-0.28}$	$2.37^{+0.29}_{-0.28}$	$4.66_{-0.55}^{+0.56}$
$R/R_{\max}(\mathbf{X}:\mathbf{Y})$	$2.06_{-0.25}^{+0.25}$	$2.06^{+0.25}_{-0.25}$	$4.13_{-0.49}^{+0.50}$	$4.13\substack{+0.50 \\ -0.49}$
$R/(1.44p_{A\to B})$	$0.71\substack{+0.09 \\ -0.08}$	$1.40^{+0.17}_{-0.17}$	$1.43^{+0.17}_{-0.17}$	$2.80^{+0.34}_{-0.33}$
1-confidence level		$1.1^{+0.4}_{-0.3} \times 10^{-2}$	$8^{+3}_{-2} \times 10^{-3}$	$1.3^{+0.5}_{-0.3} \times 10^{-7}$

Extended Data Table 4: Quantum-memory-based advantage. Distilled key rates with the asynchronous BSM device and comparison to ideal direct communication implementations, based on the performance of our network node for N = 124 and  $\langle n \rangle_m \sim 0.02$ . Distillable key rates for  $E = 0.110 \pm 0.004$  for unbiased and biased basis choice are expressed in a per-channel-occupancy and per-channel-use normalization (Methods). Enhancement is calculated versus the linear optics BSM limit ( $R_{\text{max}}(50 : 50) = p_{A \rightarrow B}/2$  for unbiased bases,  $R_{\text{max}}(99 : 1) = 0.98p_{A \rightarrow B}$  with biased bases) and versus the fundamental repeaterless channel capacity<sup>8</sup> (1.44 $p_{A \rightarrow B}$ ). Confidence levels for surpassing the latter bound<sup>8</sup> are given in the final row. 419 1. Kimble, H. J. The quantum internet. Nature 453, 1023 (2008). URL
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