Experimental Demonstration of Memory-Enhanced Quantum Communication

Supplementary Materials

Supplementary Methods

We perform all measurements in a dilution refrigerator (DR, BlueFors BF-LD250) with a base temperature of 20 mK. The DR is equipped with a superconducting vector magnet (American Magnets Inc. 6-1-1 T), a home-built free-space wide-field microscope with a cryogenic objective (Attocube LT-APO-VISIR), piezo positioners (Attocube ANPx101 and ANPx311 series), and fiber and MW feedthroughs. Tuning of the nanocavity resonance is performed using a gas condensation technique[1]. The SiV-cavity system is optically interrogated through the fiber network without any free-space optics[2]. The operating temperature of the memory node during the BSM measurements was 100-300 mK. We note that similar performance at higher temperatures should be feasible in future experiments leveraging recent developments with heavier group-IV color-centers[3] or highly strained SiV centers[4].

1 Characterization of the nanophotonic quantum memory.

A spectrum of the SiV-cavity system at large detuning (248 GHz) allows us to measure the cavity linewidth $\kappa = 21.6 \pm 1.3\,$GHz, (Extended Data Fig. 2a, blue curve) and natural SiV linewidth $\gamma = 0.123 \pm 0.010\,$GHz (Extended Data Fig. 2a, red curve). We find spectral diffusion of the SiV optical frequency to be much smaller than γ on minute timescales with an excitation photon flux of less than $1\,\mathrm{MHz}$. Next, we estimate the single-photon Rabi frequency, g, using the cavity reflection spectrum for zero atom-cavity detuning, shown in red in Extended Data Fig. 2a. For a resonant atom-cavity system probed in reflection from a single port with cavity-waveguide coupling κ_{wg}, the cavity reflection coefficient[5] as a function of probe detuning Δ_c is given by

$$r(\Delta_c) = \frac{i\Delta_c + \frac{g^2}{i\Delta_c + \frac{\gamma}{2}} - \kappa_{wg} + \frac{\kappa}{2}}{i\Delta_c + \frac{g^2}{i\Delta_c + \frac{\gamma}{2}} + \frac{\kappa}{2}}. \tag{1}$$

By fitting $|r(\Delta_c)|^2$ using known values of κ and γ, we obtain the solid red curve in Extended Data Fig. 2a which corresponds to a single-photon Rabi frequency $g = 8.38 \pm 0.05$ GHz, yielding the estimated cooperativity $C = \frac{4g^2}{\kappa\gamma} = 105 \pm 11$.

2 Microwave control

We use resonant MW pulses delivered via an on-chip coplanar waveguide (CWG) to coherently control the quantum memory[2,6]. First, we measure the spectrum of the spin-qubit transition by applying a weak, $10\,\mu$s-long microwave pulse of variable frequency, observing the optically-detected magnetic resonance (ODMR) spectrum presented in Extended Data Fig. 3a. We note that the spin-qubit transition is split by the presence of a nearby ^{13}C . While coherent control techniques can be employed to utilize the ^{13}C as an additional qubit[2,6], we do not control or initialize it in this experiment. Instead, we drive the electron spin with strong microwave pulses at a frequency f_Q such that both ^{13}C -state-specific transitions are addressed equally. This also mitigates slow spectral diffusion of the microwave transition[6] of $\sim 100\,\mathrm{kHz}$.

After fixing the MW frequency at f_Q we vary the length of this drive pulse (τ_R in Extended Data Fig. 3b) and observe full-contrast Rabi oscillations. We choose a π time of $32\,\mathrm{ns}$ in the experiments in the main text, which is a compromise of two factors: (1) it is sufficiently fast such that we can temporally multiplex between 2 and 4 time-bin qubits around each microwave π pulse and (2) it is sufficiently weak to minimize heating related effects from high microwave currents in resistive gold CWG.

With known π time we measure the coherence time of the SiV spin qubit under an XY8-1 dynamical decoupling sequence to exceed $200\,\mu\mathrm{s}$ (Extended Data Fig. 3c). In the main experiment we use decoupling sequences with more π pulses. As an example, Extended Data Fig. 3d shows the population in the $|\uparrow\rangle$ state after XY8-8 decoupling sequence (total $N_\pi = 64$ π pulses) as a function of τ, half of the inter-pulse spacing. For BSM experiments, this inter-pulse spacing, 2τ, is fixed and is matched to the time-bin interval δt. While at some times (e.g. $\tau = 64.5\,\mathrm{ns}$) there is a loss of coherence due to entanglement with the nearby $^{13}\mathrm{C}$, at $2\tau = 142\,\mathrm{ns}$ we are decoupled from this $^{13}\mathrm{C}$ and can maintain a high degree of spin coherence. Thus we chose the time-bin spacing to be 142 ns. The spin coherence at $2\tau = 142\,\mathrm{ns}$ is plotted as a function N_π in Extended Data Fig. 3d, and decreases for large N_π, primarily due to heating related effects[2].

3 Calibration of fiber network.

The total heralding efficiency η of the memory node is an important parameter since it directly affects the performance of the BSM for quantum communication experiments. One of the contributing factors is the detection quantum efficiency (QE) of the fiber-coupled SNSPDs. To estimate it we compare the performance of the SNSPDs to the specifications of calibrated conventional avalanche photodiodes single-photon counters (Laser Components COUNT-10C-FC). The estimated QEs of the SNSPDs with this method are as close to unity as we can verify. Additionally, we measure $< 1\%$ reflection from the fiber-SNSPD interface, which typically is the dominant contribution to the reduction of QE in these devices. Thus we assume the lower bound of the QE of the SNSPDs to be $\eta_{\mathrm{QE}} = 0.99$ for the rest of this section. Of course, this estimation is subject to additional systematic errors. However, the actual QE of these detectors would be a common factor (and thus drop out) in a comparison between any two physical quantum communication systems.

Here we use 2 different approaches to estimate η. We first measure the most dominant loss, which arises from the average reflectivity of the critically coupled nanophotonic cavity (Fig. 2b). While the $|\uparrow\rangle$ state is highly reflecting (94.4%), the $|\downarrow\rangle$ state reflects only 4.1% of incident photons, leading to an average device reflectivity of $\eta_{sp} = 0.493$.

In method (1), we compare the input power photodiode M1 with that of photodiode MC. This estimates a lower-bound on the tapered-fiber diamond waveguide coupling efficiency of $\eta_c = 0.930 \pm 0.017$. This error bar arises from uncertainty due to photodiode noise and does not include systematic photodiode calibration uncertainty. However, we note that if the tapered fiber is replaced by a silver-coated fiber-based retroreflector, this calibration technique extracts a coupling efficiency of $\eta_c^{cal} \approx 0.98$, which is consistent with the expected reflectivity from such a retroreflector. We independently calibrate the efficiency through the 99:1 fiber beamsplitter and the TDI to be $\eta_f = 0.934$. This gives us our first estimate on the overall heralding efficiency $\eta = \eta_{sp}\eta_c\eta_f\eta_{\mathrm{QE}} = 0.425 \pm 0.008$.

In method (2), during the experiment we compare the reflected counts from the highly-reflecting ($|\uparrow\rangle$) spin-state measured on the SNSPDs with the counts on an avalanche photodiode single photon counting module (M2 in Extended Data Fig. 1b) which has a calibrated efficiency of ≈ 0.7 relative to the SNSPDs. From this measurement, we estimate an overall efficiency of fiber-diamond coupling, as well as transmission through all relevant splices and beamsplitters of $\eta_c\eta_f = 0.864 \pm 0.010$. This error bar arises from shot noise on the single photon detectors. Overall, this gives us a consistent estimate of $\eta = \eta_{sp}\eta_c\eta_f\eta_{\mathrm{QE}} = 0.422 \pm 0.005$. Methods (1) and (2), which each have independent systematic uncertainties associated with imperfect photodetector calibrations, are consistent to within a small residual systematic uncertainty, which is noted in the text where appropriate.

4 Analysis of quantum communication experiment.

In order to achieve the lowest QBER, we routinely monitor the status trigger of the pre-selection routine and adjust the TDI (see Methods). Additionally, we keep track of the timing when the TDI piezo voltage rails. This guarantees that the SiV is always resonant with the photonic qubits and that the TDI performs high-fidelity measurements in X basis. This is implemented in software with a response time of $100\,\mathrm{ms}$.

For each experiment, we estimate the QBER averaged over all relevant basis combinations. This is equivalent to the QBER when the random bit string has all bases occurring with the same probability, (an unbiased and independent basis choice by Alice and Bob). We first note that the

QBER for positive and negative parity announcements are not independent. We illustrate this for the example, that Alice and Bob send photons in the X basis. We denote the probability P that Alice sent qubit $|\psi\rangle$, Bob sent qubit $|\xi\rangle$ and the outcome of Charlie's parity measurement is m_C, conditioned on the detection of a coincidence, as $P(\psi_A \cap \xi_B \cap m_C)$. We find for balanced inputs $P(+X_A \cap -X_B) = P(-X_A \cap +X_B)$ that $P(E_{XX}|+_C) = P(E_{XX}|-_C)$ with E_{XX} denoting the occurrence of a bit error in the sifted key of Alice and Bob. We thus find for the posterior probability L for the average QBER for XX coincidences

$$L(P(E_{XX})) = L(P(-_C| + X_A \cap +X_B)) * L(P(+_C| + X_A \cap -X_B)) \\ * L(P(+_C| - X_A \cap +X_B)) * L(P(-_C| - X_A \cap -X_B)). \quad (2)$$

Note that this expression is independent of the actual distribution of $P(\psi_A \cap \xi_B)$. Here, the posterior probability $L(P(+_C| + X_A \cap -X_B))$ is based on the a binomial likelihood function $P(N_{m_C \cap \psi_A \cap \xi_B}|N_{\psi_A \cap \xi_B}, L)$, where $N_{\mathcal{C}}$ denotes the number of occurrences with condition $\mathcal{C}$. Finally the posterior probability of the unbiased QBER is $L(P(E)) = L(P(E_{XX})) * L(P(E_{YY}))$. All values presented in the text and figures are maximum likelihood values with bounds given by the confidence interval of $\pm 34.1\%$ integrated posterior probability. Confidence levels towards a specific bound (for example, unconditional security[7]) are given by the integrated posterior probability up to the bound.

To get the ratio of the distilled distilled key rate with respect to the sifted key rate by (ideal) error correction and privacy amplification, we use the bounds given by difference in information by Alice and Bob with respect to a potential eavesdropper who performs individual attacks[8]: $r_s =$

$I(A, B) - I(A/B, E)^{\max}$. We use the full posterior probability distribution of QBER (which accounts for statistical and systematic uncertainty in our estimate) to compute the error bar on r_s, and correspondingly, the error bars on the extracted distilled key rates plotted in Fig. 4.

Supplementary References

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