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Satellite-assisted entanglement distribution with high-dimensional photonic encoding

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Abstract

Satellite-assisted entanglement distribution is a promising approach for realizing long-range quantum networking. However, the limited coherence time of existing quantum memories makes it challenging to obtain multiple event-ready entangled pairs between ground stations since one pair decoheres before the successful distribution of another. We demonstrate how this can be circumvented by pairing existing satellite-compatible spontaneous parametric down conversion (SPDC) sources with qudit-compatible quantum memories on ground. By operating the SPDC source as a source of time-bin encoded photonic qudits, simultaneous distribution of multiple entangled pairs between the ground stations can be achieved at a significantly higher rate than if the SPDC sources was operated as a source of photonic qubits. We find that for achievable coherence times of seconds and demonstrated satellite performances from the Micius satellite, the qudit operation leads to several orders of magnitude faster distribution rates than the qubit-based operation when more than one event-ready high-quality (Bell pair fidelity ≥ 0.95 as well as for fidelity ≥ 0.9) entangled pair is desired. To ensure high-quality entanglement distribution, we consider multiplexed quantum memory operation storage and, in the qubit case, we also consider storage cutoff times.

1. Introduction

Encoding information into quantum systems leads to fundamentally new capabilities for data processing and transmission [1]. Quantum key distribution (QKD) [2, 3] and blind quantum computing [4, 5] can enable information-theoretic security in communication and cloud quantum computing provided that entanglement can be established between the communicating parties. The standard approach for entanglement distribution involves sending photons through optical fibers. However, for long-distance links, satellite-assisted free space links is a promising near-term approach that circumvents the need of complex quantum repeaters to compensate transmission loss [6–11]. For example, QKD has already been demonstrated with the Micius satellite as a trusted node for distances ranging from 500 to 700 km [12, 13]. In a more advanced approach, entanglement-based QKD was achieved without relying on a trusted node, spanning distances of up to 1200 km [14], which is well outside the reach of any current fiber-based approach.

To unlock the full potential of entanglement-based quantum networking, the distribution of multiple high-quality entangled pairs will be necessary. This allows for combating noise and imperfections through entanglement purification [15, 16] as well as more advanced applications such as distributed or blind quantum computing [17, 18]. In conventional photonic qubit-based approaches, multiple pairs of photonic qubits are distributed sequentially [19] or in parallel [20, 21] and rely on a register of quantum memories to store the successful pairs until all required entangled pairs are distributed. In such schemes, the required coherence time of the quantum memories scales inversely with the transmission probability

of the photonic link, such that lower transmission directly imposes the need for proportionally longer-lived memories to maintain high-fidelity entanglement distribution [22]. To address this challenge, it has been proposed to use high-dimensional photonic qudit encoding to simultaneously entangle multiple pairs [22, 23]. However, the compatibility of such protocols with realistic satellite-based entanglement sources, as well as their comparison with other qubit-compatible techniques like temporal multiplexing [24–26] and storage-time cutoffs [27, 28], remains largely unexplored.

In this work, we propose a promising scheme for long-distance entanglement distribution where a satellite-based spontaneous parametric down conversion (SPDC) source [29, 30] is operated as an approximate source of photonic qudits to entangle two ground-based quantum memory (QM) registers. The qudit operation of the SPDC sources does not require any significant upgrade of the quantum hardware on the satellite, which we assume have similar characteristics as the Micius satellite [14]. Qudit compatible quantum memories are required for the ground nodes, which can be realized with existing hardware based on cavity-coupled diamond color centers or atomic qubits [22, 31–33].

We compare the performance of the SPDC qudit operation with the standard qubit operation considering multiplexed-memory operation in both cases and storage cutoff times for the qubit one. For the former, we assume the quantum memories can store more qubit pairs than required, which, in some cases, can result in an effectively higher distribution rate. For the latter, we assume that an entangled pair is discarded if it has been stored longer than a certain cutoff time since the quality of the entanglement will have degraded too much from decoherence. By operating with a qudit dimension that corresponds to the desired number of event-ready entangled pairs, the memories only need to store the entangled pairs for the duration of classical communication between two ground stations, to allow for an heralding signal between the ground-stations. This leads to several orders of magnitude faster distribution rates for high-fidelity entanglement distribution (Bell pair fidelity ≥ 0.90) over distances ranging from hundreds to over a thousand kilometers compared to the qubit operation for similar parameters of the source, quantum memories, and satellite link. Our results demonstrate the practical advantage of high-dimensional photonic encoding for long-range entanglement distribution using existing satellite-based quantum hardware and near-term ground-based quantum memories.

2. Model

We consider a downlink setup where photons are sent from the satellite to the ground stations, as sketched in figure 1. The goal is to establish m event-ready high-fidelity entangled pairs between two ground stations, meaning that at a certain point in time, we have m entangled pairs simultaneously available. We consider two distinct modes of operation, one using qubits and the other using qudits. In both modes, we also allow for memory multiplexing where $n \in \{0, 1, \dots\}$ specifies that nm quantum memories are available at each ground station. Note, however, that we only consider the availability of a single photonic source at the satellite such that entanglement attempts are performed sequentially and not in parallel.

In the qubit mode of operation, shown in figure 1(a), approximate entangled photonic qubit pairs are generated from an SPDC source and transmitted to the ground stations. Note that an SPDC source provides only an approximate entangled-photon pair, since the output state is a mixture of vacuum, single-pair, and higher-order multi-pair contributions, as shown in equation (1). The photonic qubits are assumed to be encoded in the time-bin basis consisting of an early or late time bin. Upon successful arrival at their respective nodes, the photons are stored in time-bin compatible quantum memories in a heralded manner. This can e.g. be achieved through spin-dependent reflection of cavity-coupled diamond defect centers or atomic quantum memories, as we will detail below. We will consider cases where the number of available memory modes is equal or greater than the required number of entangled pairs. Furthermore, we include the possibility of operating with a cutoff time such that pairs that have been stored for too long and correspondingly have been subject to too much decoherence will be discarded.

In the qudit mode of operation, depicted in figure 1(b), the SPDC source generates approximate entangled photonic qudit pairs encoded in a high-dimensional time-bin basis. We note that this merely corresponds to viewing the consecutive emission of 2^{m-1} approximate qubit pairs as an approximate 2^m dimensional qudit as we detail below. Thus, the operation of the SPDC source is in many ways exactly the same as in the qubit mode of operation. The ground-based memories will, however, need to store high-dimensional qudit states of dimension 2^m in a heralded manner. Similarly to the qubit case, multiple cavity-coupled diamond defect centers or atomic qubits can be used to achieve this. Once successfully heralded, a 2^m -dimensional photonic qudit pair generates m Bell pairs between the ground stations

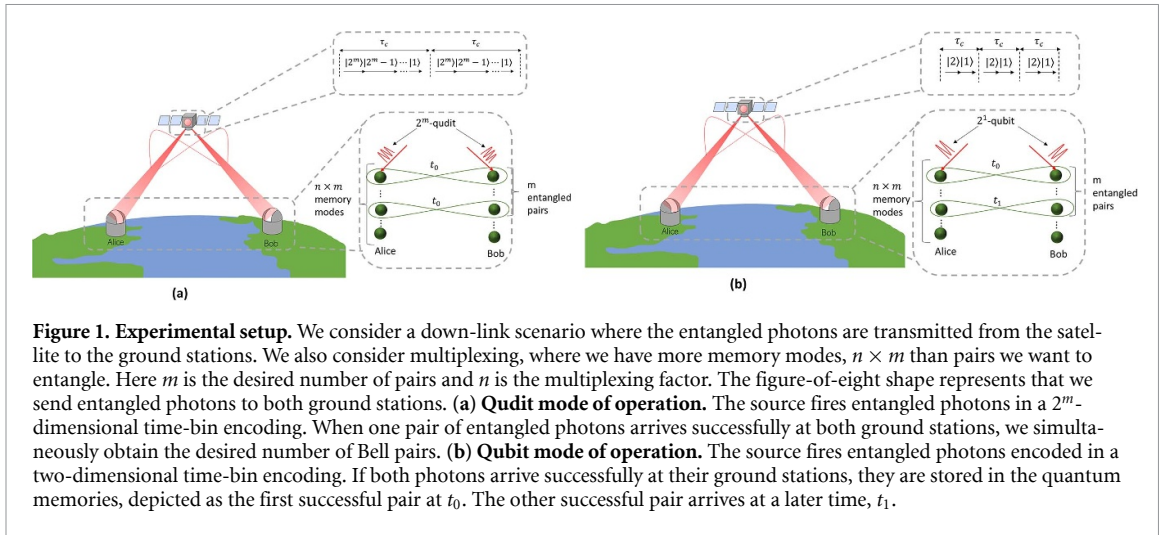


Figure 1. Experimental setup. We consider a down-link scenario where the entangled photons are transmitted from the satellite to the ground stations. We also consider multiplexing, where we have more memory modes, $n \times m$ than pairs we want to entangle. Here m is the desired number of pairs and n is the multiplexing factor. The figure-of-eight shape represents that we send entangled photons to both ground stations. **(a) Qudit mode of operation.** The source fires entangled photons in a 2^m -dimensional time-bin encoding. When one pair of entangled photons arrives successfully at both ground stations, we simultaneously obtain the desired number of Bell pairs. **(b) Qubit mode of operation.** The source fires entangled photons encoded in a two-dimensional time-bin encoding. If both photons arrive successfully at their ground stations, they are stored in the quantum memories, depicted as the first successful pair at t_0 . The other successful pair arrives at a later time, t_1 .

simultaneously. We will always consider the case where the qudit dimension matches the minimum necessary to generate m Bell pairs. For this reason, we do not consider cutoff strategies for the qudit mode of operation, but still include the possibility of having more memory modes than the required number of Bell pairs to increase the distribution rate through multiplexing.

2.1. Entangled photon pair source

We consider an SPDC source as our probabilistic source of entangled photonic pairs. A pump laser is used to drive a nonlinear optical crystal to emit time-correlated signal and idler photon pairs with a certain probability [14, 34, 35]. To generate time-bin encoded states, we consider a pulsed operation corresponding to well-defined time bins of length τ_{rep} . Two consecutive pulses generates an approximate time-bin qubit pair and, in general, 2^m consecutive pulses generates an approximate 2^m -dimensional entangled qudit pair of the form:

$$\begin{aligned}
 |\Psi\rangle_{A,B} &= \bigotimes_{l=0}^{2^m-1} \sqrt{1-\lambda^2} \sum_{n=0}^{\infty} \lambda^n |n_l, n_l\rangle_{A,B} \\
 &\approx (1-\lambda^2)^{2^m-1} \left[|0, 0\rangle_{A,B} + \lambda \sum_{l=0}^{2^m-1} |1_l, 1_l\rangle_{A,B} \right. \\
 &\quad \left. + \lambda^2 \sum_{l=0}^{2^m-1} \sum_{j \geq l}^{2^m-1} |1_l 1_j, 1_l 1_j\rangle_{A,B} + O(\lambda^3) \right], \quad (1)
 \end{aligned}$$

where the subscripts A and B correspond to two different spatial modes directed toward the ground stations of Alice and Bob respectively, and the subscripts l, j enumerate the time bins that contain photons. In other words, the state $|1_l 1_j\rangle_{A,B}$ denotes a state with photon pairs (in spatial mode A and B) in the l th and j th timebin. The parameter λ denotes the squeezing parameter, which quantifies the strength of the SPDC process and is proportional to the pump amplitude. The desired term in equation (1) is $\sum_{l=0}^{2^m-1} |1_l, 1_l\rangle_{A,B}$, which corresponds to a (not normalized) maximally entangled qudit pair of dimension 2^m .

We assume the source operates in a weak-pump regime, where the squeezing parameter is much less than one ($\lambda \ll 1$). Lowering the squeezing parameter decreases the probability of emitting a photon pair, yet improves the fidelity by reducing multi-photon events ($\propto \lambda^2$). In other words, there is a trade-off between the rate and the fidelity of entanglement which depends on the dimension of the entangled pair.

2.2. Photon transmission

Photon loss during transmission to the two ground stations will change the received state from the one emitted by the SPDC source. We model this by passing the state in equation (1) through fictitious beam splitters in each spatial mode where one output mode of the beam splitters corresponds to the loss while the other is the transmitted mode. As we detail below, we assume that the storage of the received photons in the quantum memories is heralded by the detection of the photon. Any loss and inefficiency in

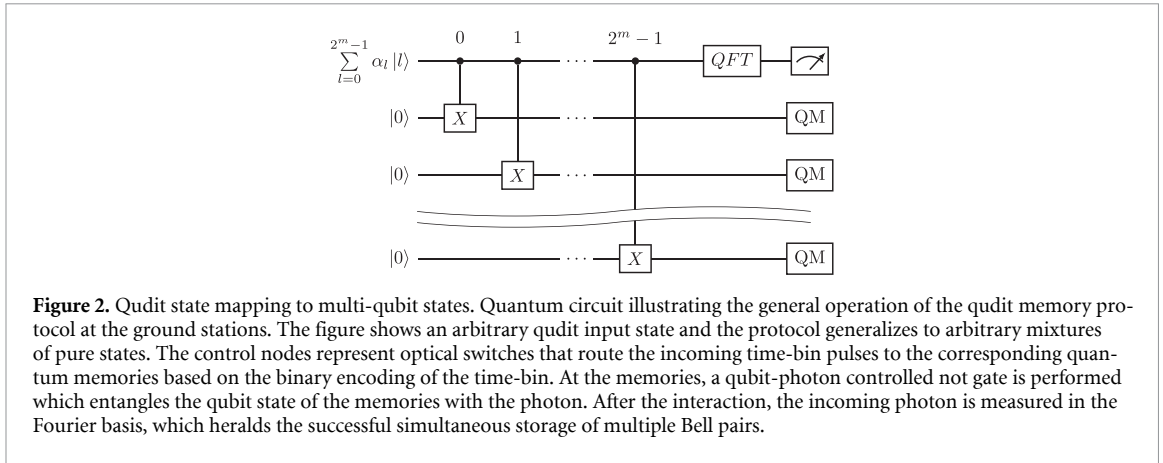


Figure 2. Qudit state mapping to multi-qubit states. Quantum circuit illustrating the general operation of the qudit memory protocol at the ground stations. The figure shows an arbitrary qudit input state and the protocol generalizes to arbitrary mixtures of pure states. The control nodes represent optical switches that route the incoming time-bin pulses to the corresponding quantum memories based on the binary encoding of the time-bin. At the memories, a qubit-photon controlled not gate is performed which entangles the qubit state of the memories with the photon. After the interaction, the incoming photon is measured in the Fourier basis, which heralds the successful simultaneous storage of multiple Bell pairs.

the memory storage process can be directly included in the effective transmission probability, p_T , of the fictitious beam splitter together with the free space transmission probability. The free space transmission probability is derived using the model in [36], which includes divergence, atmospheric absorption and pointing jitter.

Additionally, we model false detections assuming that there is a probability p_{dark} that a detector clicks despite no photon was received. We assume that this results in a stored state with zero fidelity with the desired entangled Bell pairs to have a lower bound on the Bell pair fidelity.

2.3. QM operation

Upon arrival at the ground stations, the incoming photonic state is mapped to a (multi-)qubit state in the qubit registers of the ground stations. We assume the availability of qubit-photon controlled gates, which makes the transformation

$$|\text{vac}\rangle_{\text{ph}}|0\rangle \rightarrow |\text{vac}\rangle_{\text{ph}}|0\rangle, \quad |1\rangle_{\text{ph}}|0\rangle \rightarrow |1\rangle_{\text{ph}}|1\rangle, \quad (2)$$

where $|\text{vac}\rangle_{\text{ph}}$ ($|1\rangle_{\text{ph}}$) denotes the absence (presence) of a photon in a particular mode. Such gates can be implemented with existing hardware of cavity-coupled diamond color centers [31, 32] or atomic qubits [33, 37] and can be used to store 2^m dimensional photonic qudits in m qubits in a heralded manner with the protocol of [22]. Here, we sketch the main steps of this protocol and note that it also works for photonic qubits ($m = 1$).

To simplify the explanation, we consider only the desired component of the photon state in equation (1):

$$|\Psi\rangle = \frac{1}{\sqrt{2^m}} \sum_{l=0}^{2^m-1} |l\rangle_{A,\text{ph}} |l\rangle_{B,\text{ph}}. \quad (3)$$

At both Alice and Bobs side, the corresponding qudit interacts with m cavity-coupled qubit memories. Which of the m qubit memories the photon interacts with depends on the specific time-bin and is controlled by photonic switching. The switching is programmed according to the binary representation of the time bins (see figure 2). Here the X -gate represents the Pauli- X matrix, $\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, applied to the corresponding qubit register which is subsequently stored in a QM. The QFT represents the quantum Fourier transform that is applied to the qudit to facilitate the generalized X -basis measurement needed to herald the arrival of the photon while erasing the which time-bin information. Consequently, the decimal time-bin encoding of the 2^m -dimensional qudits in equation (3) will be transformed into the corresponding binary encoding in m qubits. A 2^m -dimensional qudit state represented by $|l\rangle$ ($l = 0, 1, \dots, 2^m - 1$) can be changed to binary encoding by the following conversion: $[l]_{10} = [l_{m-1} \dots l_k \dots l_1 l_0]_2$ ($l_i \in \{0, 1\}$) [22]. For example, the number 5_{10} is mapped to 101_2 in binary encoding.

The m -qubit register is initialized in the $|0\rangle^{\otimes m}$ state, and the incoming photon flips the qubits corresponding to its binary-encoded state. If $l_i = 1$ the i th qubit of the register will flip from $|0\rangle$ to $|1\rangle$. If $l_i = 0$ the qubit remains in state $|0\rangle$. After interaction at both ground stations, the resulting state of the

qudit and qubit memory registers is:

$$|\psi\rangle = \frac{1}{\sqrt{2^m}} \sum_{l=0}^{2^m-1} |l\rangle_{A,\text{ph}} |l\rangle_{B,\text{ph}} |l_2\rangle_A |l_2\rangle_B, \quad (4)$$

where $|l_2\rangle$ represents the state of the multi-qubit register in binary encoding. The successful storage of the qudit information in the qubit registers is completed by detecting the photonic modes in a generalized X -basis such that the information about which time-bin the photons were in is erased. Such a measurement can be implemented by applying local QFTs to the photonic modes at the ground stations, which can be implemented with optical delay lines, beam splitters and phase shifters as outlined in [22, 38]. It corresponds to projecting the photonic modes onto basis states of the form

$$|X_k\rangle = \frac{1}{\sqrt{2^m}} \sum_{l=0}^{2^m-1} e^{2i\pi lk/2^m} |l\rangle, \quad (5)$$

where $k \in \{0, 1, \dots, 2^m - 1\}$. The measurement also heralds the successful transfer of the qudit information to the qubit register i.e. that a photon was received. Up to local phases determined by the measurement outcomes at Bob and Alice, the qubit register state following detection will be:

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|0, 0\rangle_{A,B} + |1, 1\rangle_{A,B})^{\otimes m}. \quad (6)$$

To confirm the success of both sides, the measurement outcomes must be communicated between Alice and Bob. During this time, referred to as the heralding time, τ_h , the stored qubits experience decoherence. Additionally, in the qubit case, when more than one event-ready entangled pair is desired, the already entangled pairs need to wait until all desired pairs have been successfully entangled during which they also suffer from decoherence. We model this as a depolarizing channel where the quantum state decays to a mixed state over time (t), with a decoherence probability of $1 - e^{-t/T_{\text{coh}}}$. Here, T_{coh} is the coherence time of the memories.

Besides the limited coherence time of the qubit registers, additional errors such as photon loss and imperfect spin-photon gates will also affect the performance of the qubit registers. The photon loss can be directly absorbed into the overall photon transmission probability as previously described. Imperfect spin-photon gates and photonic switching affect the quality of the generated Bell pairs in a non-trivial way, which is treated in detail in [38]. In particular, the qudit encoding can result in correlated errors between the Bell pairs, which is a clear distinction between the qubit and the qudit mode of operation considered here. As shown in [38], the effect of such correlated errors depends on the application; purification schemes are able to effectively target such correlated errors while quantum error correction codes are less effective. Since the focus of this work is to study the effect of limited coherence time of the qubit registers as well as the approximate entangled pair source, we will assume that these are the dominant errors and neglect the effect of other imperfections in the qubit register storage for now. This will allow us to provide general, hardware-agnostic bounds on the performance of both the qubit and qudit operation of a satellite-based SPDC source for long-distance entanglement distribution.

3. Performance

To compute the rate of entanglement distribution, we need to estimate the rate of photons successfully mapped to the qubit registers at the ground stations in both the qubit and qudit mode of operation. However, for the following analysis, the qubit mode of operation can be viewed as a special example of a two-dimensional qudit.

The length of a photonic time-bin is set by the repetition rate of the pump laser, r_{rep} . Consequently, an approximate qudit pair of the form in equation (1) is emitted at a rate of $r_{\text{rep}}/2^m$. If a detector clicks at a ground station, which ideally heralds a successful storage, the receiver will close the access to the qubits involved and send a (classical) heralding signal to the other ground station. If no signal has been received from the other ground station after the heralding time τ_h has elapsed (time of communication between the ground stations), the qubits will be immediately reset in order to receive photons again. Additionally, if a heralding signal for the corresponding qubits at the other ground station is received within the communication time, the qubits will also be immediately reset. A successful entanglement will only happen when the qubit pairs are available in both ground stations and heralding clicks are simultaneously recorded so that the ground stations both receive a heralding signal at the same time. Thus,

the probability of successful entanglement distribution is given by $p_{\text{ent}} = p_{\text{suc}}\pi_{(0,0)}$, where p_{suc} denotes the probability that a single qudit pair is successfully transmitted and mapped onto the qubit registers, assuming the qubits are available, and $\pi_{(0,0)}$ represents the probability that the qubits are indeed available. We calculate the latter probability using a Markov chain [39].

To increase the entanglement distribution rate, we consider a multiplexing scheme, where there are more available quantum memories than the desired number of entangled pairs. In particular, if m entangled pairs are desired, we define a multiplexing parameter $n \in \{0, 1, \dots\}$ that specifies that mn qubit memories are available at each ground station. We will count one entanglement generation attempt as attempting all mn qubit memories sequentially. Thus, the time of one attempt is $\tau_c = 2mn/r_{\text{rep}}$ ($\tau_c = 2^m n/r_{\text{rep}}$) for the qubit (qudit) mode of operation. Additionally, we are in the limit $p_{\text{suc}} \ll 1$ and we will therefore consider a slightly sub-optimal protocol where we only allow for a single heralding click per attempt. In other words, we discard events with more than a single heralding click per attempt. However, the probability of multiple heralding clicks is very low for practically relevant parameters, meaning that including such events would not significantly increase the rate. The fact that p_{suc} is so small is a consequence of the physical regime in which the protocol operates to generate high-fidelity entangled pairs. In order to maintain high-fidelity entangled photon pair generation, the squeezing parameter λ of the SPDC source must be kept small to suppress higher-order multi-photon emissions, which would otherwise degrade the fidelity of the entangled state. As a result, the probability of successfully generating the desired single entangled photon pair (p_{ent}) is inherently small, due both to the low pair-generation probability from the SPDC source and the limited transmission probability through the atmosphere. This ensures that multiple-click events are extremely rare, and we therefore only include 2nd order photon emissions in our analysis.

We estimate the average rate of the entanglement distribution from the average number of attempts, $\langle A \rangle$ to obtain the desired number of event-ready entangled pairs:

$$R = \frac{1}{\langle A \rangle \tau_c}. \quad (7)$$

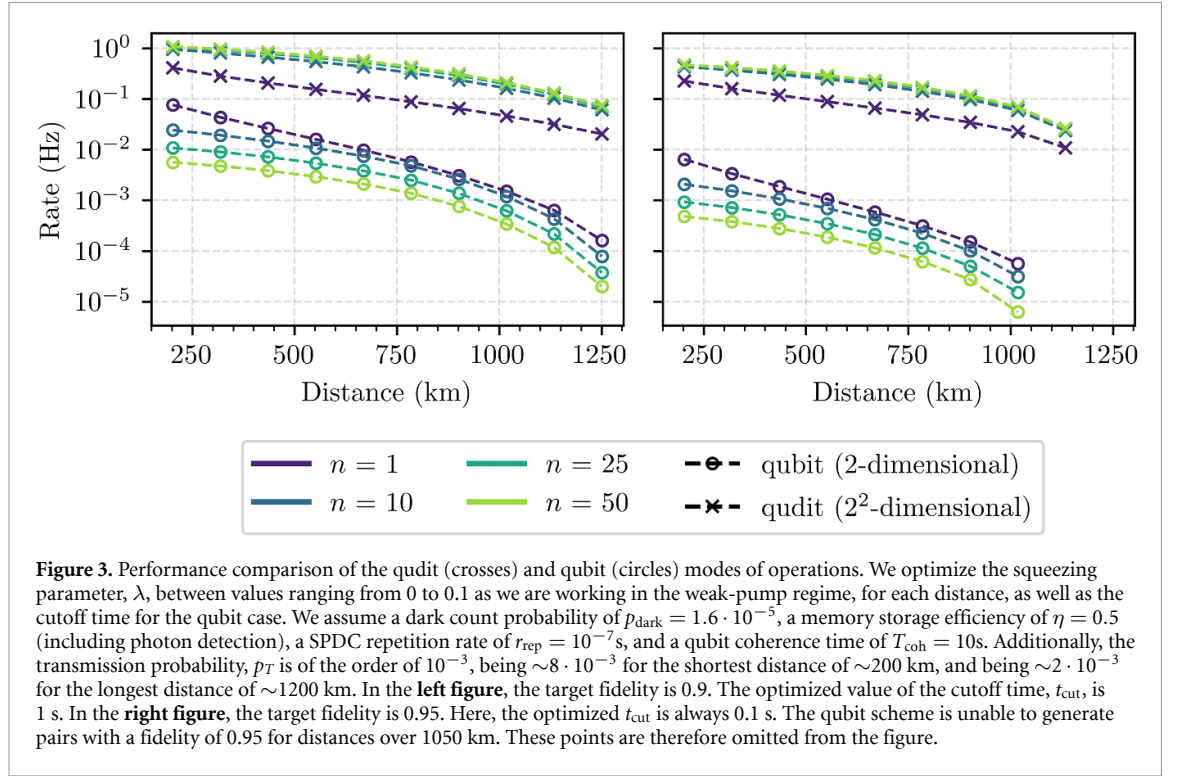
To calculate $\langle A \rangle$, it is useful to define the parameters D and N to keep track of the many possible combinations of obtaining m entangled pairs across multiple attempts. In the qubit (qudit) mode of operation $D = mn$ ($D = n$) and $N = m$ ($N = 1$). Since we have at most one heralding click per attempt, the average number of attempts to get m entangled pairs can be estimated as:

$$\begin{aligned} \langle A \rangle &= \frac{D!}{(D-N)! p_{\text{approx}}^N} p_{\text{ent}}^N \sum_{i_1=0}^{\infty} \cdots \sum_{i_N > i_{N-1}}^{\infty} (i_1 + 1 \\ &\quad + \sum_{k=2}^N (i_k - i_{k-1})) (1 - p_{\text{ent}})^{(D-N+1)i_N + D - N + \sum_{k=1}^{N-1} i_k} \\ &= N + \sum_{k=1}^N \frac{(1 - p_{\text{ent}})^{D+1-k}}{1 - (1 - p_{\text{ent}})^{D+1-k}}. \end{aligned} \quad (8)$$

This expression is valid both in the qubit and qudit mode of operation with the suitable choices of D and N . It captures that in each attempt i_j , we go through all the available memories. As the probability of entanglement is small, we discard the events in which more than one pair is entangled in a single attempt. To account for all possible combinations where there are no simultaneous successes, we sum over these combinations with condition $i_k > i_{k-1}$ to ensure that each pair needs a different number of attempts. The term $1 - p_{\text{approx}}$ is the probability of obtaining m entangled pairs with more than one heralding click per attempt. This can be calculated as:

$$\begin{aligned} p_{\text{approx}} &= \frac{D!}{(D-N)!} p_{\text{ent}}^N (1 - p_{\text{ent}})^{ND - [(N-1)^2 + 2]} \\ &\quad \times \sum_{i_1=0}^{\infty} \cdots \sum_{i_N=0}^{\infty} (1 - p_{\text{ent}})^{\sum_{k=1}^N (D+1-k)}. \end{aligned} \quad (9)$$

As stated above $p_{\text{ent}} = p_{\text{suc}}\pi_{(0,0)}$. In our simulations, we keep $1 - p_{\text{approx}} < 1\%$, which ensures that we do not significantly reduce the rate by discarding events with multiple heralding clicks in one attempt.



To compute the average fidelity of the entangled pairs, we take into account the effects of decoherence during the waiting period for all pairs to become successfully entangled

$$\begin{aligned}
 \langle F(t) \rangle = & \frac{D!}{N \cdot (D-N)! p_{\text{approx}}} p_{\text{ent}}^N (1 - p_{\text{ent}})^{ND - ((N-1)^2 + 2)} \\
 & \times \sum_{i_1=0}^{\infty} \cdots \sum_{i_N=0}^{\infty} \left[(1 - p_{\text{ent}})^{\sum_{k=1}^N (D+1-k) i_k} \right. \\
 & \times (F(\tau_h) + F(\tau_h + (i_N + 1) \tau_c) + \cdots \\
 & \left. + F\left(\tau_h + \tau_c \sum_{j=2}^N (i_j + 1)\right) \right], \quad (10)
 \end{aligned}$$

where $F(t)$ is the fidelity of a pair after storage time t . The detailed expression for $F(t)$ can be found in appendix A, which also includes infidelities from higher-order photon terms and dark counts. Note that we assume a worst-case scenario in which these events result in states with fidelity of zero with the desired Bell states. The ordering used in equation (10) means that the i_N 'th pair is the last pair that gets entangled and consequently, it only decoheres for the heralding time τ_h . On the other hand, the first pair (i_1) has to wait the longest, namely for $\tau_h + \tau_c \sum_{k=2}^N i_k$, where i_k is the number of entanglement attempts needed for the k th pair to be successfully entangled.

The previous expressions for the average rate and fidelity of the entangled pairs (equations (8) and (10)), do not operate with a cutoff time. In the qubit scheme, we add a cutoff time, $t_{\text{cut}} < T_{\text{coh}}$, to the memories to ensure a certain target fidelity of the entangled pairs. We consider a strategy where once the first pair has been entangled, it will be stored in the QM the chosen cutoff time, and the rest of the pairs we want to entangle must be successfully entangled within that time. To account for this in our expression of the rate and the fidelity, the sums over the attempts that occur after the first successfully entangled pair will be bounded by the cutoff time. The updated expressions including the cutoff time can be found in appendix B for the case of $m = 2$. Tables 1 and 2 show all the parameters assumed for our numerical analysis. The transmission probabilities, needed for the calculation of p_{suc} , are calculated following the model of [36].

In figure 3, we show a comparison between the qudit and the qubit mode of operation when requiring a minimum average Bell pair fidelity of 0.90 (left figure) and 0.95 (right figure) of two event-ready entangled pairs ($m = 2$). For the qubit mode of operation we optimize the cutoff time to achieve the maximum distribution rate for a certain distance. We assume the same performance in terms of memory

efficiency and coherence time for both modes of operation and optimize the squeezing parameter λ to achieve the highest distribution rate. Our results show that the qudit mode of operation results in orders of magnitude larger distribution rates than the qubit mode. We also see that multiplexing increases the distribution rate for the qudit case while it surprisingly does not for the qubit mode of operation. This is because the attempt time increases as we increase the factor of multiplexing and the increase in success probability is not significant enough to outweigh this. In other words, multiplexing is worth implementing, if the rate at which the photons arrive at the ground stations, is higher than the communication time between them, which is not the case for the Micius parameters considered here where the SPDC source rate is 10 MHz. Note that increasing the repetition rate of the SPDC source would eventually result in a rate boost from multiplexing also in the qubit case.

Additionally, from figure 3, we see that the use of four-dimensional qudits enables entanglement distribution of two Bell pairs with fidelity $\geq 90\%$ over distances of up to 1250 km at which point the line of sight covered by the satellite also becomes a limiting factor. However, we see that, at this maximum distance, the entanglement rate drops to zero when the target fidelity is 0.95. The fidelity depends not only on the coherence time and the waiting time for the successful entanglement of all pairs, but also on the squeezing parameter (λ), the transmission probability (p_T), the memory efficiency (η), and the dark count probability (p_{dark}). In the simulations, the squeezing parameter is optimized to achieve the highest rate under the chosen fidelity cap. However, for distances ≥ 1250 km, it becomes impossible to find a squeezing parameter that ensures a target fidelity of 0.95 due to dark counts. This can be improved by improving the overall transmission probability. The transmission probability is influenced by factors such as the satellite's altitude and the size of its transmitters. Detection efficiency, on the other hand, can be enhanced by improving the detectors at ground stations. Therefore, while maintaining the same satellite, upgrading the ground station's detection systems could enable entanglement over even greater distances.

So far, we have focused on the simultaneous distribution of two Bell pairs, which would enable key objectives as entanglement purification. If more Bell pairs are desired the qudit dimension should be increased accordingly to allow for their simultaneous generation. While the analysis of the qudit protocol is straightforward for $m \geq 3$ Bell pairs, more complex cutoff strategies become available for the qubit protocol. In particular, some Bell pairs may now be discarded while others are still kept in memory. Investigating these more complex strategies becomes significantly more challenging from a computational standpoint. Unlike the analytical treatment possible for $m = 2$, it seems necessary for $m \geq 3$ to rely on numerical simulations to fully capture the stochastic dynamics of entanglement generation, memory decoherence, and cutoff decisions. Given the regime of very low entanglement success probabilities of satellite-to-ground scenarios we consider, such simulations would require very long runtimes to yield statistically meaningful results. For this reason, we have chosen not to pursue an explicit study of dynamic cutoff strategies in this work.

Instead, we performed a comparison to a qubit protocol without cutoffs (see appendix C) investigating how the fidelity drops with distance when maintaining a distribution rate of 0.01 HZ for obtaining $m = 2, 3, 4, 5$ simultaneously available Bell pairs. We find that while the qudit protocol is capable of maintaining an average Bell pair fidelity $\gtrsim 90\%$, the average fidelity of the qubit protocol is below 50% for the simulation parameters listed in table 1. Consequently, cutoff strategies will be needed to maintain high fidelity for the qubit operation, which will inevitable result in a decrease in rate as demonstrated in figure 3 for $m = 2$.

We have deliberately kept our analysis of the detection side of the protocol general to enable a broadly applicable and fair comparison between the qubit and qudit protocols. Depending on the ground station implementation, frequency conversion might be required to interface with certain memory platforms, introducing additional loss. Our error model includes losses during transmission, imperfections of the SPDC source from multi-photon emissions, QM decoherence, and a general detection efficiency parameter η . We note that local loss from the QM operations originating from, e.g. optical switches and cavity scattering can be absorbed into this general efficiency parameter.

Arguably one can expect additional error sources from the qubit memory operation which will be dependent on the concrete physical implementation. One possible implementation with optical switches is outlined in [22] but more near-term implementations without optical switches are also possible as described in [38]. As previously mentioned, cavity-coupled diamond color centers and atoms represents a near-term hardware suitable for operation as heralded qudit memories [18, 31–33]. The effect of various errors such as cavity scattering errors in the spin-photon CZ gate, imperfections in qudit generation, dephasing of the photonic qudit, qubit gate errors, spin-qubit decoherence, and photon losses on the qudit memory operation with such hardware has previously been analyzed in [22, 38]. Importantly, from their analysis, we see that the effect of switching loss and imperfect cavity-scattering only scale logarithmically with the qudit dimension. The numerical analysis in [38] shows that errors at the few percent

Table 1. All relevant parameters used in our simulations are shown here for convenience. T_{coh} represents the coherence time of the quantum memories in our model, t_{rep} defines the repetition time of the SPDC emitter, h_{sat} is the orbital height of the satellite considered, η denotes the detection efficiency at the ground stations, p_{dark} is the dark count probability which gives the probability of getting a click in the detector without a photon emitted by our source being present, λ_{photon} is the wavelength of the emitted photons, r_g is the diameter of the ground stations aperture, and r_s gives the diameter of the satellite aperture. These were mostly adopted from [14, 34]. The parameter of the coherence time is based on what has been accomplished with cavity-coupled diamond color centers, as shown in [40, 41].

Constant	Value
T_{coh}	10s
t_{rep}	$1.7 \cdot 10^{-7}$ s
h_{sat}	500 km
η	0.5
p_{dark}	$1.6 \cdot 10^{-5}$
λ_{photon}	810 nm
r_g	0.6
r_s	0.15

Table 2. Distances and corresponding transmission probabilities, calculated using the model from [36].

Distance (km)	Transmission probability
202	0.008 4818
319	0.008 0688
435	0.007 5628
552	0.006 9541
668	0.006 2768
785	0.005 5368
901	0.004 7536
1018	0.003 9591
1134	0.003 1964
1251	0.002 5067

level for the cavity-mediated spin-photon gates as well as single qubit gate errors of $\sim 0.1\%$ are compatible with generation of two Bell pairs with an average fidelity $\gtrsim 90\%$. Additionally, the effect of correlated errors in the memory operation was also studied in [38], where it was shown that they can be effectively mitigated by an optimized purification circuit. Quantitatively, for the generation of two entangled pairs ($m = 2$) with errors at the percent level, [38] shows that the fidelity can be increased from around 90% to about 93.5% after purification, whereas in the case of four pairs ($m = 4$), purification can boost the fidelity from 74% to about 96%.

4. Conclusion

In summary, we have shown how satellite-assisted entanglement distribution can benefit significantly from adopting a qudit mode of operation when multiple, high-fidelity, and event-ready entangled pairs are desired. Our simulations show that a qudit mode of operation results in several orders of magnitude higher distribution rates than a standard qubit mode of operation for all distances between 200 and 1200 km. Importantly, the qudit mode of operation does not require any substantial upgrades of existing quantum satellites payloads but rather upgrades of the quantum memories at the ground nodes, which are much more accessible. To achieve a general bound on the achievable rate, we have assumed

negligible infidelities from the memory storage operation, except for the effect of limited coherence time. Although errors in current hardware do not quite satisfy this assumption for the target fidelities of 90% and 95% assumed in this work, we note that recent experiments with cavity-coupled diamond color centers have demonstrated spin-photon gates with infidelities of $\sim 2\%$, qubit gate errors of $\sim 1\%$ and measurement errors of $\sim 1\% - 2\%$ [18] together with single photon storage efficiencies of $\sim 40\%$ [31] with clear paths to improvement. Additionally, using nearby nuclear memory spins, coherence times on the order of seconds have been demonstrated with the same hardware [40, 41], with the possibility to extend the coherence time to the order of minutes using weakly coupled nuclear spins [42]. We also note that [18] reports entanglement generation between two SiV qubit memories using a photonic qudit demonstrating the compatibility of this hardware with photonic qudits. This makes it conceivable that satellite-assisted high-quality entanglement distribution using the qudit mode of operation considered in this work could be realized with near-term hardware.

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Data availability statement

The code and data of the results of this paper are openly available on 4TU.ResearchData: ‘Data underlying the publication ‘Satellite-assisted Entanglement Distribution with High-Dimensional Photonic Encoding’, at <https://doi.org/10.4121/61ca8a5b-3af2-4947-904c-36c21b4ed090> [43].

Appendix A. Fidelity

To calculate the fidelity of the entangled pairs at the ground stations, we consider the density matrix, ρ , that describes the states of the memories following a successful heralding signal i.e. where both ground stations recorded a single click (detectors are not assumed to be number resolving). We consider the emitted states of the SPDC up to the third order ($\mathcal{O}(\lambda^3)$). To obtain a lower bound on the fidelity, we assume that only the state corresponding to the desired first-order excitations from the SPDC source, which is successfully transmitted and detected by both ground stations result in a non-zero overlap with the desired Bell state, $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$. We consider a single entangled pair of memories by tracing over all other memory qubits, which provides us the following expression for ρ :

$$\begin{aligned} \rho = & \frac{1}{p_{\text{click}}} \left(2^m p_T^2 \eta^2 \lambda^2 \rho_{\text{pair}} + (2^{m-1} (2^m + 1) p_T^4 \lambda^4 \eta^4 \right. \\ & + 2^{m+1} p_T \eta (1 - p_T \eta) \lambda^2 p_{\text{dark}} + 2^m (2^m + 1) p_T^2 \eta^2 \\ & \times (1 - p_T \eta)^2 \lambda^4 (p_{\text{dark}} + 2) + 2^{m+1} (2^m + 1) \\ & \times (p_T^3 \eta^3 (1 - p_T \eta) \lambda^4 + p_T \eta (1 - p_T \eta)^3 \lambda^4 p_{\text{dark}}) \\ & + p_{\text{dark}}^2 \left(2^{m-1} (2^m + 1) (1 - p_T \eta)^4 \lambda^4 \right. \\ & \left. \left. + 2^m (1 - p_T \eta)^2 \lambda^2 + 1 \right) + \mathcal{O}(\lambda^6) \right) \rho_{\text{garbage}}, \end{aligned} \quad (\text{A1})$$

where p_{click} is the probability of the successful heralding signal corresponding to the normalization constant of the matrix. The first term represents the desired first-order excited state of the SPDC source, which prepared the memories in the state ρ_{pair} , while the rest of the terms correspond to error terms from higher order transmissions and dark counts in the detectors. We model these as resulting in a density matrix ρ_{garbage} , which has zero overlap with the desired Bell state. As stated in the main text, λ is the excitation probability of the SPDC source, p_T is the total transmission probability, and η is the combined the memory storage and detector efficiency.

The fidelity can now be expressed as:

$$F(t) = \frac{\langle \Phi^+ | \rho_{\text{pair}} | \Phi^+ \rangle}{\text{Tr}(\rho)}, \quad (\text{A2})$$

where:

$$\begin{aligned} \langle \Psi^+ | \rho_{\text{pair}} | \Psi^+ \rangle &= \frac{1}{p_{\text{click}}} 2^m p_T^2 \eta^2 \lambda^2 \left(\left(e^{-t/T_A} + \left(1 - e^{-t/T_A} \right) \epsilon_1 \right) \right. \\ &\quad \times \left(e^{-t/T_B} + \left(1 - e^{-t/T_B} \right) \epsilon_1 \right) + \left(1 - e^{-t/T_A} \right) \\ &\quad \times \left. \left(1 - e^{-t/T_B} \right) \left(\epsilon_x^2 + \epsilon_y^2 + \epsilon_z^2 \right) \right), \end{aligned} \quad (\text{A3})$$

and

$$\begin{aligned} \text{Tr}(\rho) &= \frac{1}{p_{\text{click}}} \left(2^m p_T^2 \eta^2 \lambda^2 + 2^{m-1} (2^m + 1) p_T^4 \lambda^4 \eta^4 \right. \\ &\quad + 2^{m+1} p_T \eta (1 - p_T \eta) \lambda^2 p_{\text{dark}} + 2^m (2^m + 1) p_T^2 \eta^2 \\ &\quad \times (1 - p_T \eta)^2 \lambda^4 (p_{\text{dark}} + 2) + 2^{m+1} (2^m + 1) \\ &\quad \times \left(p_T^3 \eta^3 (1 - p_T \eta) \lambda^4 + p_T \eta (1 - p_T \eta)^3 \lambda^4 p_{\text{dark}} \right) \\ &\quad + p_{\text{dark}}^2 \left(2^{m-1} (2^m + 1) (1 - p_T \eta)^4 \lambda^4 \right. \\ &\quad \left. \left. + 2^m (1 - p_T \eta)^2 \lambda^2 + 1 \right) + \mathcal{O}(\lambda^6) \right). \end{aligned} \quad (\text{A4})$$

Here, we have applied a general decoherence channel on the memory qubits where with probability $1 - e^{-t/T_A}$ ($1 - e^{-t/T_B}$), an X , Y , or Z Pauli matrix or an Identity matrix is applied to Alice's (Bob's) qubit with relative probabilities ϵ_x , ϵ_y , ϵ_z , and ϵ_1 . The time the pair is stored before the successful entanglement of all desired pairs is achieved is t . Note that this varies from pair to pair in the qubit mode of operation as shown in equation (10), while $t = t_h$ in the qudit mode of operation. In general, the coherence times T_A and T_B of Alice's and Bob's memory qubits could be different, however, we set both decoherence times to $T_A = T_B = T_{\text{coh}}$ in our simulations. Furthermore, we assume that the decoherence channel corresponds to a full depolarizing channel with $\epsilon_1 = \epsilon_x = \epsilon_y = \epsilon_z = 1/4$.

Appendix B. Cutoff time calculation

Here, we show how we estimate the rate and fidelity for the qubit mode of operation when we have cutoff time and we want to entangle two pairs. In this scheme, the second pair needs to be entangled within the cutoff time, otherwise, the first entangled pair is discarded and we repeat the process again. To estimate the average number of attempts to successfully entangle two pairs within the cutoff time, we consider the average number of tries assuming a successful entanglement generation i.e. that the pairs are generated within the cutoff time, $\langle n_{\text{succ}} \rangle$. The expression for this is similar to the one shown in equation (8), except that the sum over the second pair, i_2 , is bounded by a finite number of tries, N_{cut} , which is calculated using the cutoff time. This number of tries is defined as $N_{\text{cut}} = t_{\text{cut}}/D\tau_c$, where t_{cut} is the cutoff time, which is always smaller than the decoherence time of the quantum memories. Specifically,

$$\begin{aligned} [b] \langle n_{\text{succ}} \rangle &= \frac{D!}{(D-2)! p_{2p}} p_{\text{ent}}^2 (1 - p_{\text{ent}})^{(2D-3)} \\ &\quad \times \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{N_{\text{cut}}-2} (i_1 + i_2 + 2) (1 - p_{\text{ent}})^{i_2(D-1) + D i_1}, \end{aligned} \quad (\text{B1})$$

where p_{2p} is given by

$$\begin{aligned} [b] p_{2p} &= \frac{D!}{(D-2)!} p_{\text{ent}}^2 (1 - p_{\text{ent}})^{(2D-3)} \\ &\quad \times \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{N_{\text{cut}}-2} (1 - p_{\text{ent}})^{i_2(D-1) + D i_1}, \end{aligned}$$

and is the probability of successfully entangling two pairs within the cutoff time. Note that we still only allow for a single success per attempt as described in the main text. To estimate the average number of attempts, we also estimate the average number of attempts to obtain one entangled pair but fail to entangle the second one within the cutoff time, $\langle n_{\text{fail}} \rangle$, as well as the probability of this event, p_{fail} . This is given by

$$[b] \langle n_{\text{fail}} \rangle = N_{\text{cut}} + \langle n_1 \rangle = \frac{D!}{(D-1)!} p_{\text{ent}} (1 - p_{\text{ent}})^{D-2} \sum_{i_1=0}^{\infty} (i_1 + 1) (1 - p_{\text{ent}})^{Di_1} + N_{\text{cut}},$$

where $\langle n_1 \rangle$ is the average number of attempts to get the first pair. The probability of a failed attempt is $p_{\text{fail}} = (1 - p_{\text{ent}})^{N_{\text{cut}}}$.

We now estimate the average number of attempts to successfully entangle two pairs within the cutoff time as

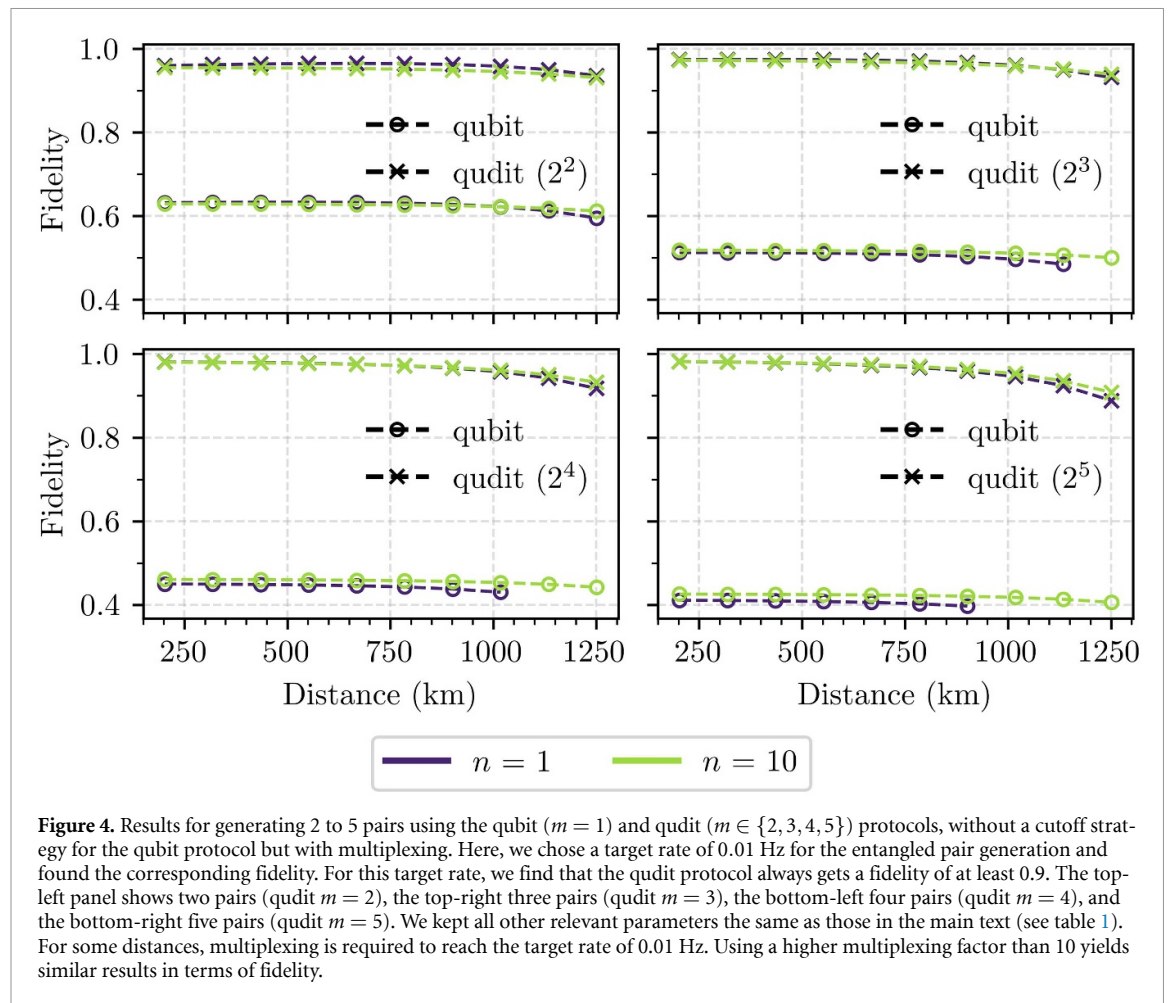
$$\begin{aligned} [b] \langle n \rangle &= \sum_{i=0}^{\infty} (i \langle n_{\text{fail}} \rangle + \langle n_{\text{succ}} \rangle) p_{\text{fail}}^i p_{\text{succ}} \\ &= \frac{1}{p_{\text{succ}}} ((\langle n_{\text{fail}} \rangle - \langle n_{\text{succ}} \rangle) p_{\text{fail}} + \langle n_{\text{succ}} \rangle), \end{aligned} \quad (\text{B2})$$

where $p_{\text{succ}} = 1 - p_{\text{fail}}$. We note that $p_{\text{succ}} \approx p_{2p}$ for the parameters considered, as the probability of heralding two pairs in the same attempt is very small. For the computation of the fidelity, we also truncate the upper limit of the sum for i_2

$$\begin{aligned} [b] \langle F(t) \rangle &= \frac{D!}{2(D-2)! p_{2p}} p_{\text{ent}}^2 (1 - p_{\text{ent}})^{2D-3} \\ &\times \sum_{i_1=0}^{\infty} \sum_{i_2=0}^{N_{\text{cut}}-2} (1 - p_{\text{ent}})^{i_2(D-1)+Di_1} [F(\tau_h) + F(\tau_h + (i_2 + 1)\tau_c)]. \end{aligned}$$

Appendix C. $m \geq 2$ simulations

Here, we substantiate our claims that the qudit protocol outperforms a qubit protocol in many cases by adding simulations for higher dimensions, since we focused on generating two entangled pairs in the main text. For the simulations in figure 4, we are not considering a cutoff time for the qubit mode of operation to limit the computational complexity. When a rate of 0.01 Hz is desired, we find that the qudit protocol can generate high-fidelity entangled pairs up to 1250 km and at least up to 5 pairs, whereas the qubit protocol can not generate high-fidelity pairs for this rate. In order to generate high-quality pairs, concessions with respect to the desired rate have to be made when using the qubit protocol. We also find that without the use of multiplexing, the qubit protocol is not able to reach the desired rate at larger distances. Considering a cutoff strategy to increase the fidelity will lead to even lower rates for the qubit protocol. All in all, our results show that the qudit protocol outperforms the qubit protocol for generating 2 to 5 pairs of entangled qubits. This trend is expected to continue for any arbitrary number of desired pairs, but it will come at the cost of a more complex implementation.



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