

Quantum entanglement distribution via uplink satellite channels

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Significant work has been done to develop quantum satellites, which generate entangled pairs in space and distribute them to ground stations separated some distance away. The reverse “uplink” case, where pairs are generated on the ground and swapped on the satellite using an optical Bell measurement, has not been seriously considered due to a prevailing assumption that it is practically infeasible. In this paper, we illustrate the feasibility of performing Discrete Variable photonic Bell measurements in space by conducting a detailed numerical analysis to estimate the channel efficiency and attainable pair fidelity for various satellite-station configurations. Our model accounts for a wide range of physical effects such as atmospheric effects, stray photons, and mode mismatch. Our findings show promise toward the feasibility of photonic Bell measurements in space, which motivates future research toward large-scale satellite-based uplink entanglement distribution.

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I. INTRODUCTION

Distributed entanglement is a crucial resource for quantum communications and distributed quantum computing [1–8]. Using satellites to generate and distribute entanglement to distant ground stations has previously been considered in the contexts of global communication networks [9] and resource estimation for fault-tolerant distributed quantum computing [10]. In particular, the latter work demonstrated that the limited power available to quantum satellites sets a hard limit on the scalability of satellite-based distributed quantum computing in the *downlink* case. One potential way to improve scalability is to consider the reverse *uplink* case where the Bell pairs are generated on the ground and then sent to the satellite where they are swapped via Bell measurement. On the ground, we can allocate significantly more power to pair production (from MW to GW [11]) than we can on a satellite (around 10 kW [12]). This has the potential to not only enhance Bell-pair generation rates significantly, but also make the satellite lighter and simpler in design [13].

The idea of transferring quantum states from ground to satellite (i.e., via uplink channels) has been previously explored both theoretically and experimentally in both discrete and continuous variables largely for quantum key distribution (QKD) and quantum teleportation [13–20]. A discussion on

dual channel uplink transmission for entanglement swapping has been made for continuous variable states [21], but a corresponding discussion with discrete variable photonic states for designing satellite-based repeaters has not yet been made prior to this article because several disadvantages, despite the power advantage, have dissuaded serious consideration of this method.

The first is that uplink channel attenuation is larger than downlink attenuation since atmospheric scattering occurs at the start of the transmission, unlike downlink where it happens in the end [18,19,22]. Additionally, the aperture size of a satellite’s receiving telescope is considerably smaller than what is possible on the ground. Due to this, the uplink protocol requires high-precision clock synchronization and satellite positioning [23] for precisely pointing and aiming the photons at a moving satellite and facilitating the near-simultaneous arrival of the two photons required for a successful Bell measurement. The above disadvantages pose serious questions on the feasibility of performing successful Bell measurements on the satellite using ground-to-satellite links. Therefore, as a first step toward answering the bigger question of whether the advantages of large power stations on the ground can overpower the disadvantages discussed above, we first need to demonstrate the feasibility of performing Bell measurement on the satellite. In this paper, we demonstrate that the uplink Bell measurements are indeed feasible. This is the first step toward considering realizable practical entanglement distribution with uplink satellite links.

We first introduce our uplink setup and the various physical phenomena affecting the Bell measurement, such as beam widening, beam wandering, atmospheric turbulence and attenuation, stray photons, and mode mismatch. We ignore polarization error as it is less than 0.001 rad (0.06%) [24,25],

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which is negligible. We also ignore the Doppler effect [26,27] as it can be compensated by precisely measuring the potential wavelength shift based on the trajectory and calibrating the photon wavelength accordingly [28]. Then, we combine all these phenomena to derive expressions for Fidelity and Efficiency of the protocol. Next, we compare these metrics against various important parameters, for which we use a realistic range of values. Finally, we discuss our results and potential future directions toward the realization of uplink satellite networks. A detailed derivation of the Fidelity and Efficiency expressions can be found in the Supplemental Material, which, along with the *Mathematica* code containing the simulations, can be found at [29,30].

II. THE PROTOCOL

Setup. Our setup consists of two ground stations separated by a distance D_G with a satellite orbiting overhead in the low-Earth-orbit region (Fig. 1). For our setup, we fix the satellite equidistant from the two ground stations. At each ground station, we consider a Bell-pair generator that generates perfect Bell pairs, i.e., with a fidelity of 1. One half of this pair is encoded in the polarization basis of a photon, and the other half is encoded in a physical qubit of an arbitrary quantum computing architecture installed at the ground station. The photons at each station are fired up toward the satellite, where they will be entanglement swapped via optical Bell measurement (Fig. 1, inset). This is implemented with the use of a PBS followed by an optical Hadamard (i.e., a 45° wave plate) and two polarization-resolving photon detectors. Each of these detectors themselves are made of a polarizing beam splitter followed by two photodetectors. A successful outcome is determined when the satellite detects two clicks—one at each mode. This entangles the two computational qubits at the ground stations.

III. MODE-MATCHING MODEL

Mode mismatch. Every photon has probability of a wave packet associated with it. During optical Bell measurements, the two incoming photons must arrive at the satellite simultaneously; i.e., the wave packets of the two incoming photons should spatiotemporally align. We call this mode matching [31,32]. Any spatiotemporal mismatch between the two wave packets leads to increased distinguishability between the two photons, thus leading to reduced fidelity of the swapped Bell pairs on the ground. To reduce the effect of mode mismatch, we employ time gating, i.e., a short, limited time window when the photon detectors are switched on. This allows only a fraction of the wave packets to be detected, thus decreasing their distinguishability and reducing the probability of successful measurement. Therefore, the choice of the length of the gating window depends upon the acceptable trade-off between fidelity and success probability of the measurement.

A photon in free space located at position x_0 is described by the Gaussian wave packet ψ centered at x_0 , given by [33]

$$\psi(x) = \left(\frac{1}{2\pi\sigma^2} \right)^{\frac{1}{4}} e^{-\frac{1}{4} \left(\frac{x-x_0}{\sigma} \right)^2} e^{ik(x-x_0)}, \quad \sigma = c\sigma_t, \quad (1)$$

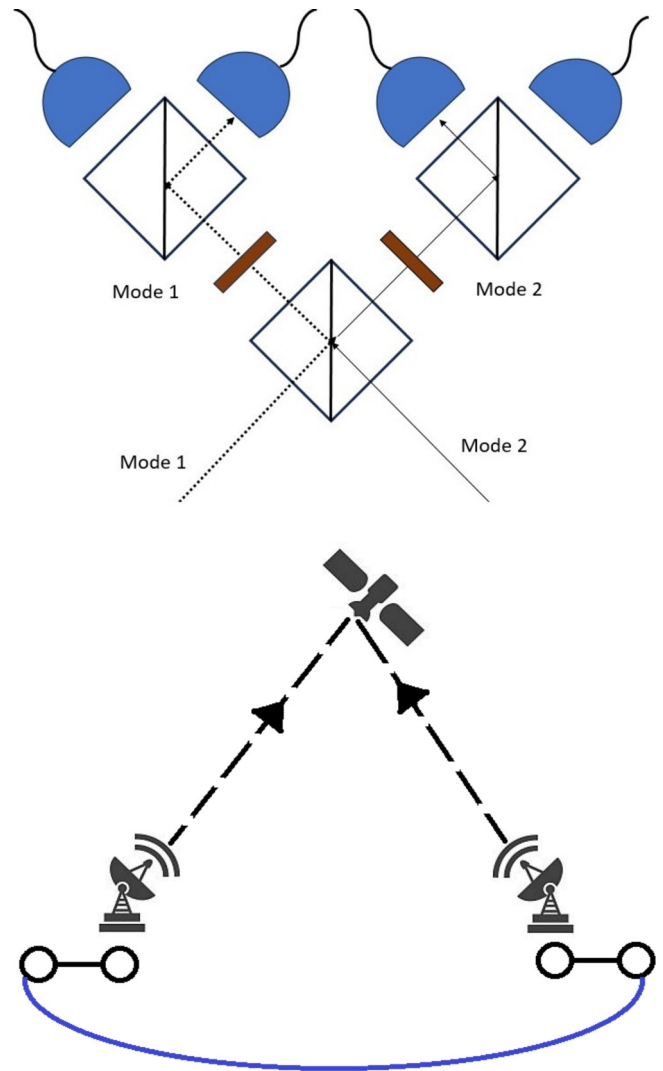


FIG. 1. (Bottom) A schematic of the proposed uplink setup. The setup consists of two ground stations sending one half of their Bell pairs to a satellite via an uplink channel. The Bell measurement happens on the satellite, entangling the other two ground photons (represented by the dark blue curvy line). (Top) The Bell-measurement apparatus inside the satellite. The apparatus consists of two optical modes, directed by a Polarizing Beam Splitter (PBS), followed by two 45° polarizers (one on each mode), and further followed by two PBSs, one on each mode, and four bucket detectors, one on each output of the final PBSs.

where σ_t is the temporal width of the wavepacket [34,35] (i.e., the standard deviation of the Gaussian), $k = 2\pi/\lambda$ is the wave number (where λ is the wavelength of the ground photon), and c is the speed of light. Consider the two incoming photons from the two ground stations whose associated wave packets are ψ_1 and ψ_2 , respectively. Let us say these photons are incident on the satellite at times t_1 and t_2 . This leads to a temporal mismatch $\Delta t = t_2 - t_1$ between the two photons, which can also be interpreted as the path difference Δx , such that $\Delta x = c\Delta t$ and therefore $\psi_2(x) = \psi_1(x + \Delta x)$. For the moment, let us assume that we have an ideal photon channel with mode mismatch being the only phenomenon affecting our protocol. Let $t_{\min}$ and $t_{\max}$ be the opening and closing times of the gating

window, i.e., the switch-on time and the switch-off time of the detector, respectively. Then, the probability P_{gw} that the photon entering mode i passes through the gating window is given by (see Sec. 4 of the Supplemental Material [30])

$$P_{gw_i} = \int_{ct_{\min}}^{ct_{\max}} |\psi_i(x)|^2 dx. \quad (2)$$

The fidelity F_{ic} of the resulting swapped Bell pair is given by

$$F_{ic} = \frac{1}{2} + \frac{\left| \int_{ct_{\min}}^{ct_{\max}} \psi_1(x) \psi_2^*(x) dx \right|^2}{2P_{gw_1} P_{gw_2}}. \quad (3)$$

IV. ERRORS DUE TO BEAM WIDENING AND WANDERING

Beam widening and beam wandering. Beam widening and beam wandering are significant phenomena affecting efficiency in satellite communications. [18,19,36–40]. Beam widening is an intrinsic phenomenon where the width of the beam gradually increases with travel, making the overall beam conical [41–44], while beam wandering is a phenomenon where the beam centroid randomly and continuously shifts as it passes through the atmosphere due to changing refractive index of the atmosphere caused by turbulence [18,36,45]. If R_A is the radius of aperture of the receiving telescope and w is the width of the beam due to the combined effects of beam widening and wandering (not to be confused with the width σ of the probability wave packet of the photons), then the channel efficiency η_w due to beam widening and wandering is given by [18,19,46]

$$\eta_w = 1 - e^{-2R_A^2/(w^2 + 10^{-12}z^2 + \sigma_{tr}^2)}, \quad (4)$$

where $10^{-12}z^2$ is the pointing error of the transmitter [18] and σ_{tr} is the tracking error in satellite's position, and w is the overall long-term beam width due to the combined effects of beam widening and wandering [18] (see Sec. 5.2 of the Supplemental Material [30]).

V. ATMOSPHERIC ATTENUATION

Atmospheric attenuation. The channel efficiency η_a resulting solely due to atmospheric attenuation is given by [18]

$$\eta_a(h, \theta) = \exp \left[-\alpha_0 \int_0^{z(h, \theta)} \exp \left[-\frac{h(y, \theta)}{\tilde{h}} \right] dy \right], \quad (5)$$

where h is the satellite altitude, and $\alpha_0 = 5 \times 10^{-6} \text{ m}^{-1}$ and $\tilde{h} = 6600 \text{ m}$ are constants [47,48].

VI. STRAY PHOTONS AND NOISE

Stray photons. There are various sources of stray photon we need to account for in our analysis [17,19,49–52]. Earth's surface emits numerous stray photons into space from its reflected sunlight in the daytime and from reflected moonlight and Earth's own blackbody radiation in the nighttime [18,19,50]. These stray photons, when incident on the satellite along with the legitimate photons, can lead to corrupted measurements. Let r_{day} and r_{night} be the rates of stray photons incident on the photodetectors during daytime and nighttime,

respectively. Within a time-gating window t of the detector (where $t = t_{\max} - t_{\min}$) (not to be confused with Δt , which is the path difference between the two photonic wave packets divided by c), the probability P_{SP} that n stray photons are incident on a single detector follows the Poissonian distribution:

$$P_{SP}(n) = \frac{(r_{\text{day/night}}t)^n e^{-r_{\text{day/night}}t}}{n!}. \quad (6)$$

The detailed derivation of r_{day} and r_{night} is provided in Sec. 6 of the Supplemental Material [30].

VII. DUAL UPLINK CHANNEL EFFICIENCY

Overall success probability. In our measurement setup (Fig. 1), we have four detectors 1, 2, 3, and 4. Let the tuple $d = (d_1, d_2, d_3, d_4)$ denote the detection outcomes, with $d_i = \{0, 1\}$ for detector i , where 0 represents no click whereas 1 represents a click. Here d_1 and d_2 represent left-hand mode, and d_3 and d_4 represent right-hand modes. The probability that photons from the ground stations cause a detection event according to tuple d is $P_G(d)$. The probability that stray photons will cause detector clicks according to tuple d is $P_D(d)$. $P_G(d)$ and $P_D(d)$ incorporate all the losses described above (see the Supplemental Material [30]). The measurement signature M is given by the bitwise AND of bit strings associated with G and D . The allowed accepted signatures are $M = (1, 0, 1, 0)$, $(1, 0, 0, 1)$, $(0, 1, 1, 0)$, and $(0, 1, 0, 1)$. These are legitimate signatures because there is one photon detected in each of the spatially resolved modes. Consider one success signature $M = (1, 0, 1, 0)$. The probability P_M of this happening is (see Sec. 7 of the Supplemental Material [30])

$$\begin{aligned} P_M(1, 0, 1, 0) &= P_G(1, 0, 1, 0)[P_D(0, 0, 0, 0) + P_D(0, 0, 1, 0) \\ &\quad + P_D(1, 0, 0, 0) + P_D(1, 0, 1, 0)] \\ &\quad + P_G(0, 0, 1, 0)[P_D(1, 0, 0, 0) + P_D(1, 0, 1, 0)] \\ &\quad + P_G(1, 0, 0, 0)[P_D(0, 0, 1, 0) + P_D(1, 0, 1, 0)] \\ &\quad + P_G(0, 0, 0, 0)P_D(1, 0, 1, 0). \end{aligned} \quad (7)$$

Assuming that the four detectors are equally configured, it can be verified that all four legitimate signatures are symmetric. Therefore, the total probability η_{tot} of successful signature for any given photon pair coming from the ground stations (or equivalently the uplink dual-channel efficiency) is given by

$$\eta_{\text{tot}} = 4P_M(1, 0, 1, 0). \quad (8)$$

VIII. PRACTICAL FIDELITY

Overall fidelity. Let the probability of a legitimate coincidence given the success signature M be P_S . In case of an illegitimate coincidence, the resulting state is considered to be maximally mixed ($I/4$). Therefore, the actual fidelity F of the resulting swapped Bell pair is given by (see Sec. 8 of the Supplemental Material [30])

$$F = P_S F_{ic} + (1 - P_S)/4. \quad (9)$$

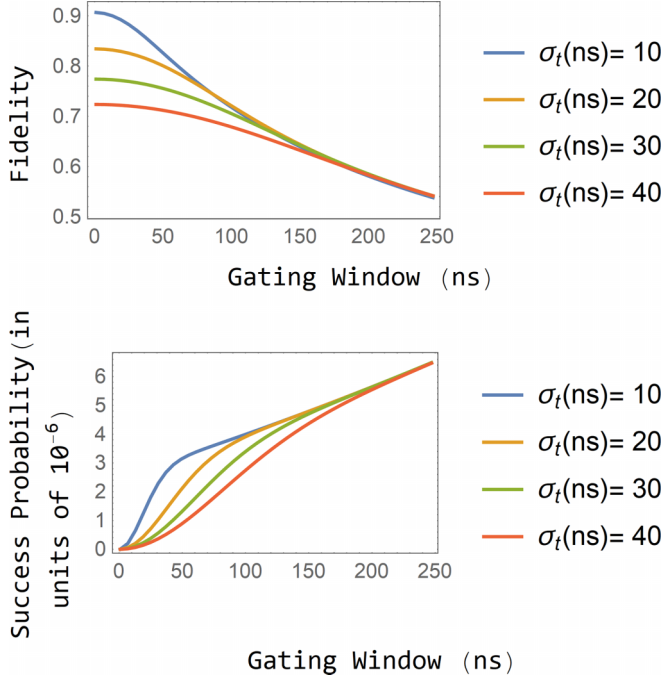


FIG. 2. Fidelity F and success probability η_{tot} vs time-gating window for various wave packet widths σ_t (in ns). The satellite altitude is taken to be 500 km and the ground stations are separated by a distance of 1000 km. All other parameters are chosen according to Table S1 of the Supplemental Material [30].

IX. RESULTS AND DISCUSSION

Results and analysis. For our analysis, we consider the snapshot of the instant where the satellite is equidistant from the two ground stations. We are just considering the symmetry snapshot to simplify our calculations. In nonsymmetric cases and cases that deviate from the symmetric snapshot, we assume that the satellite trajectory be precalculated and photon release times and directions at the ground stations be appropriately adjusted to sync the photon arrival times at the satellite. This prevents any additional mode mismatch due to asymmetry. Therefore, all mode mismatch would be purely stemming from the limited precision in clock synchronization between the ground stations and the satellite.

To study how success probability (8) and fidelity (9) behave, we consider realistic parameter values chosen from various experiments and industry standards (see Table S1 and Sec. 9 of the Supplemental Material [30]). We organize our simulation around four main quantities of interest: temporal wave packet width σ_t , time-gating window $t = t_{\text{max}} - t_{\text{min}}$, satellite altitude h , and distance D_G between ground stations. The first two quantities have a large range of experimentally realizable values and affect the overall fidelity and η_{tot} non-trivially; therefore, their trends must be examined to establish a reasonable range of values for these parameters. Following this, we characterize the range of distances and satellite altitudes across which the protocol can produce feasible results.

Can our uplink protocol work during daytime? The short answer is no: Our simulations show that the fidelity is around 0.25 due to excess stray photons, which makes our protocol

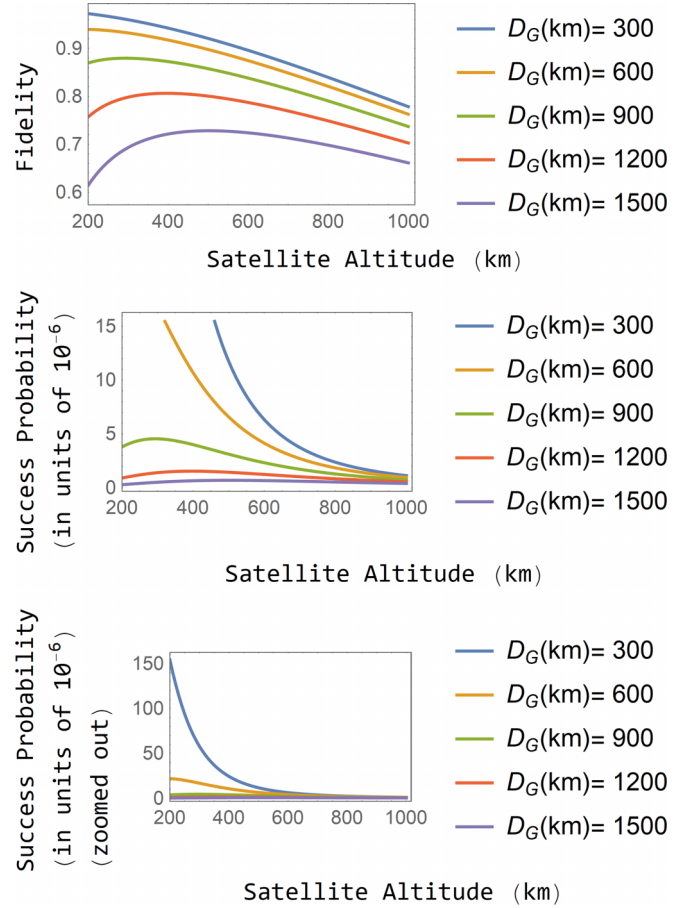


FIG. 3. Fidelity F and success probability η_{tot} vs satellite altitude for various ground station separations. The third plot is the y-axis enlarged version of the second plot, just to wholly extend the trends at $D_G = 300$ km and $D_G = 600$ km. Here, we have taken the temporal wave packet width to be 10 ns and the time-gating window to be 40 ns. All other parameters are chosen according to Table S1 of the Supplemental Material [30].

infeasible during daytime. From now on, we focus on night-time operation.

Behavior concerning gating window and wave packet widths (Fig. 2). As the gating window widens, more stray photons start hitting the detector and reducing the probability of legitimate coincidences, and also the distinguishability between the two ground photon wave packets increases, therefore decreasing the fidelity. With increasing gating window, more of the wave packets and the stray photons are let in, which increases the overall success probability. For a given gating window, increasing the wave packet width decreases the overall amount of wave packet being captured by the gating window, leading to lesser fidelity and lower success probability.

Behavior concerning satellite altitude and ground station separations (Fig. 3). Our theoretical model predicts fidelity to decrease with satellite altitude and distance of ground stations. Initially with rising satellite altitude, the photons from the ground stations have to pass through the lesser and lesser atmosphere due to decreasing zenith angle, increasing both the fidelity and the success probability. With further increase

in satellite altitude, the atmosphere begins to matter less as it becomes only a small part of the photon's journey, and the loss due to the widening of the beam's cross-sectional width w starts dominating, which reduces both the fidelity and the success probability. Increasing the ground separations rapidly decreases the fidelity and success probability because with increasing ground separation, the overall photon travel paths increase, leading to longer travel, resulting in greater attenuations.

Best performance. Optimizing the design of entanglement distribution in the framework of our protocol is a challenging task because the problem is a nonlinear optimization. Nevertheless, the most performant protocol we can reach is with a gating window of 40 ns, wave packet width of 10 ns, satellite altitude of 200 km, and ground separation of 300 km: This protocol distributes entangled state at a fidelity of 0.972 with a success probability of 1.5×10^{-4} . Nonetheless, even with a satellite altitude of 500 km and a ground separation as far as 1000 km, we can obtain fidelity of 0.84 and a success probability of 2.404×10^{-6} .

X. CONCLUSION

Our analysis of uplink entanglement distribution shows feasibility only in nighttime achieving high-fidelity entangled

state between two ground stations with efficiencies on the order of 10^{-6} . This shows promising results to motivate us to consider satellites as potential Bell-measurement devices for entanglement distribution. We assume on-demand photon generators, but they are not experimentally of sufficient quality. Pulsed pumping generates photons probabilistically, but due to this, it is difficult to synchronize the two-photon generators at the two ground stations. The next stage of research would be to explore this aspect and also the scalability of uplink entanglement swapping by evaluating the hardware capabilities and limitations concerning multiplexing the protocol to leverage the advantage of mammoth power capabilities on the ground as compared to the satellite. Following multiplexing, a synchronization protocol [53,54] needs to be established to tag the photons for correct entanglement swapping.

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Correction: Author name Alexander S. Solnstev has been changed to Alexander S. Solntsev.