Spooky Action at a Global Distance – Resource-Rate Analysis of a Space-Based Entanglement-Distribution Network for the Quantum Internet

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Recent experimental breakthroughs in satellite quantum communications have opened up the possibility of creating a global quantum internet using satellite links. This approach appears to be particularly viable in the near term, due to the lower attenuation of optical signals from satellite to ground, and due to the currently short coherence times of quantum memories. These drawbacks prevent ground-based entanglement distribution using atmospheric or optical-fiber links at high rates over long distances. In this work, we propose a global-scale quantum internet consisting of a constellation of orbiting satellites that provides a continuous on-demand entanglement distribution service to ground stations. The satellites can also function as untrusted nodes for the purpose of long-distance quantum-key distribution. We determine the optimal resource cost of such a network for obtaining continuous global coverage. We also analyze the performance of the network in terms of achievable entanglement-distribution rates and compare these rates to those that can be obtained using ground-based quantum-repeater networks.

I. INTRODUCTION

One of the most remarkable applications of quantum mechanics is the ability to perform secure communication via quantum-key distribution (QKD) [1–4]. While current global communication systems rely on computational security and are breakable with a quantum computer [5–7], QKD offers, in principle, unconditional (information-theoretic) security even against quantum computers. With several metropolitan-scale QKD systems already in place [8–15], and with the development of quantum computers proceeding at a steady pace [16–18], the time is right to begin transitioning to a global quantum communications network before full-scale quantum computers render current communication systems defenseless [19–21]. In addition to QKD, a global quantum communications network, or quantum internet, would allow for the execution of other quantum-information-processing tasks, such as quantum teleportation [22, 23], quantum clock synchronization [24–26], distributed quantum computation [27], and distributed quantum metrology and sensing [28–30].

Building the quantum internet is a major experimental challenge [31–34]. All of the aforementioned tasks make use of shared entanglement between distant locations on the earth, which is typically distributed using single-photonic qubits sent through either the atmosphere or optical fibers. These schemes require reliable single-photon sources, quantum memories with high coherence times, and quantum gate operations with low error. It is well known that optical signals transmitted through either the atmosphere or optical fibers undergo an exponential decrease in the transmission success probability with distance [35, 36]. Quantum repeaters [37–39] have been proposed to overcome this exponential loss by dividing the transmission line into smaller segments along which errors and loss can be corrected using entanglement swapping [22, 40] and entanglement purification [41–43]. Several theoretical proposals for quantum repeater schemes based on quantum error correction and quantum memories have been made (see Refs. [39, 44, 45] and references therein); however, many of these proposals have resource requirements that are currently unavailable. Furthermore, experimental demonstrations performed so far have been limited [46–48] and do not scale to the distances needed to realize a global-scale quantum internet.

Satellites have been recognized as one of the best methods for achieving global-scale quantum communication with current or near-term resources [32, 49–53]. This advantage is due to the fact that the majority of the optical path traversed by an entangled photon pair is in free space, resulting in lower loss compared to ground-based entanglement distribution over atmospheric or fiber-optic links. Satellites can also be used to implement long-distance QKD with

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untrusted nodes, which is missing from most current implementations of long-distance QKD, due to the lack of a quantum repeater. A satellite-based approach also allows for the possibility to use quantum strategies for tasks such as establishing a robust and secure international time scale via a quantum network of clocks [54], to extend the baseline of telescopes for improved astronomical imaging [55–57], and to explore fundamental physics [58, 59].

Several proposals for satellite-based quantum networks have been made that use satellite-to-ground transmission, ground-to-satellite transmission, or both [49, 60–68]. Recent experiments [64, 69–75] between a handful of nodes opens up the possibility of building a global-scale quantum internet using satellites. As shown in Fig. 1, this means having a constellation of orbiting satellites with continuous global coverage that transmit either bipartite or multipartite entanglement to ground stations. These ground stations can act as hubs that then distribute entanglement to neighboring ground stations via short ground-based links. Ideally, the satellite network should have continuous global coverage and provide entanglement on demand. Some basic questions arise when considering building a such a satellite-based quantum internet: How many satellites are needed to achieve continuous global coverage at rates that outperform ground-based quantum-repeater setups? At what altitude should the satellites be placed in order to achieve these rates?

In this work, we analyze a global-scale quantum internet architecture in which satellites act as entanglement sources that distribute entangled photon pairs to ground stations. The nearest-neighbor entangled links can then be extended via entanglement swapping to obtain shared entanglement over longer distances. We determine the required number of satellites for such a network to have continuous global coverage. Since satellites are a costly resource, continuous global coverage should be achieved with as few satellites as possible. To that end, we define a cost function that allows us to investigate the trade-off between the number of satellites, their altitude, the average loss over a 24-hour period, and the average entanglement-distribution rates. By optimizing our cost function, we obtain the optimal number of satellites for continuous global coverage, as well as the optimal altitude at which the satellites should be placed such that the average loss is below a certain threshold. We compare the resulting entanglement-distribution rates to those obtained via ground-based entanglement distribution assisted by quantum repeaters. We find that the satellite-based scheme (without quantum repeaters) can outperform ground-based quantum repeater schemes.

II. NETWORK ARCHITECTURE

Our proposed satellite network architecture is illustrated in Fig. 2. We consider $N_R$ equally spaced rings of satellites in polar orbits. We allow for $N_S$ equally-spaced satellites in each ring, so that there are $N_R N_S$ satellites in total, all of which are at the same altitude $h$. The satellites act as source stations that transmit pairs of entangled photons to line-of-sight ground stations for the purpose of establishing elementary links. The ground stations act as quantum repeaters in this scheme – performing entanglement purification and entanglement swapping once the elementary
FIG. 2. We consider a global-scale satellite-based quantum network in which there are $N_R$ equally-spaced rings of satellites. Within each ring, there are $N_S$ satellites in polar orbits.

links have been established. In this way, we execute long-distance entanglement distribution between ground stations. Note that we could alternatively use the satellites as quantum repeaters, which would require uplinks. It has been shown in, e.g., Ref. [62] that uplinks are more lossy and lead to lower key rates for QKD. For this reason, we consider downlinks only. The photon sources on the satellites produce polarization-entangled photon pairs. State-of-the-art sources of entangled photons are capable of producing polarization-entangled photons on a chip with a fidelity up to 0.97 [79–82].

The transmission of photons from satellites to ground stations is modeled well by a bosonic pure-loss channel with transmittance $\eta_{sg}$ [83]. For single-photon polarization qubits (with a dual-rail encoding), transmission through the pure-loss channel corresponds to an erasure channel [84]. That is, given a single-photon polarization density matrix $\rho$, the evolution of $\rho$ through the quantum channel $N_{sg}$ is given as

$$N_{sg}(\rho) = \eta_{sg} \rho + (1 - \eta_{sg}) |0\rangle\langle 0| \tag{1}$$

where $|0\rangle\langle 0|$ is the vacuum state. Hence, with probability $\eta_{sg}$, the dual-rail qubit is successfully transmitted and with probability $1 - \eta_{sg}$ the qubit is lost. For the transmission of a pair of single-photon dual-rail qubits, let $\eta_{sg}^{(1)}$ and $\eta_{sg}^{(2)}$ be the transmittances of the two qubits. Then, with probability $\eta_{sg}^{(1)} \eta_{sg}^{(2)}$, both qubits are successfully transmitted and with probability $1 - \eta_{sg}^{(1)} \eta_{sg}^{(2)}$ at least one of the qubits is lost [85].

The transmittance $\eta_{sg}$ generally depends on atmospheric conditions (such as turbulence and weather conditions) and on orbital parameters (such as altitude and zenith angle) [86, 87]. In general, we can decompose $\eta_{sg}$ as

$$\eta_{sg} = \eta_{fs} \eta_{atm} \tag{2}$$

where $\eta_{fs}$ is the free-space and $\eta_{atm}$ is the atmospheric transmittance. Free-space loss occurs from diffraction (i.e., beam broadening) over the channel and the use of finite-sized apertures at the receiving end. This effect causes $\eta_{fs}$ to scale as the inverse-distance squared in the far-field regime. Atmospheric loss occurs due to absorption and scattering in the atmosphere and scales exponentially with distance as a result of the Beer-Lambert law [36, 88, 89]. However, since atmospheric absorption is relevant only in a 10–20 km thick layer above the earth’s surface [36], free-space diffraction is the main source of loss in space-based quantum communication. In order to characterize the free-space and atmospheric transmittances with simple analytic expressions, we ignore turbulence-induced effects in the lower atmosphere, such as beam profile distortion, beam broadening (prominent for uplink communication [36, 62]), and beam wandering (see, e.g., Ref. [87]). Note that turbulence effects can be corrected using classical adaptive optics [36]. We also ignore the inhomogeneous density profile of the atmosphere, which can lead to path elongation effects at large zenith angles. A comprehensive analysis of loss without these approximations can be found in Refs. [87, 89].

Consider the lowest-order Gaussian spatial mode for an optical beam traveling a distance $L$ between the sender and receiver with a circular receiving aperture of radius $r$. Then the free-space transmittance $\eta_{fs}$ is given by [35]

$$\eta_{fs}(L) = 1 - \exp \left( - \frac{2r^2}{w(L)^2} \right) , \tag{3}$$
Parameter | Definition | Value
---|---|---
\(r\) | Receiving aperture radius | 0.5 m
\(w_0\) | Initial beam waist | 2.5 cm
\(\lambda\) | Wavelength of satellite-to-ground signals | 810 nm
\(\eta_{\text{atm}}\) | Atmospheric transmittance at zenith | 0.5 at 810 nm [62]

TABLE I. Parameters used in the modeling of loss from satellites to ground stations.

FIG. 3. The total optical transmittance from satellites to ground stations is given by \(\eta_{gs} = \eta_{fs}\eta_{\text{atm}}\), where the free-space transmittance \(\eta_{fs}\) given by Eq. 3, and the atmospheric transmittance \(\eta_{\text{atm}}\) is given by Eq. 5. (Left) Two ground stations \(g_1\) and \(g_2\) are separated by a distance \(d\) with a satellite at altitude \(h\) at the midpoint. Both ground stations are the same distance \(L\) away from the satellite, so that the total transmittance for two-qubit entanglement transmission (one qubit to each ground station) is \(\eta_{gs}^2\). (Right) Plot of the transmittance \(\eta_{gs}^2\) as a function of \(d\) for various satellite altitudes.

where

\[
w(L) := w_0\sqrt{1 + \left(\frac{L}{L_R}\right)^2}\]  

(4)

is the beam waist at a distance \(L\) from the focal region \((L = 0)\), \(L_R := \pi w_0^2\lambda^{-1}\) is the Rayleigh range, \(\lambda\) is the wavelength of the optical mode, and \(w_0\) is the initial beam-waist radius.

We model the atmosphere as a homogeneous absorptive layer of finite thickness in order to characterize \(\eta_{\text{atm}}\). Uniformity of the atmospheric layer then implies uniform absorption (at a given wavelength), such that \(\eta_{\text{atm}}\) depends
only on the optical path traversed through the atmosphere. Under these assumptions, and using the Beer-Lambert law \[88\], for small zenith angles we have that

\[
\eta_{\text{atm}}(L, h) = \begin{cases} 
(\eta_{\text{atm}}^{\text{zen}} \sec \zeta), & \text{if } -\frac{\pi}{2} < \zeta < \frac{\pi}{2}, \\
0, & \text{if } |\zeta| > \frac{\pi}{2}, 
\end{cases}
\]

(5)

with \(\eta_{\text{atm}}^{\text{zen}}\) the transmittance at zenith (\(\zeta = 0\)). For \(|\zeta| > \frac{\pi}{2}\), we set \(\eta_{\text{atm}} = 0\), because the satellite is over the horizon and thus out of sight. The zenith angle \(\zeta\) is given by

\[
\cos \zeta = \frac{h}{L} - \frac{1}{2} \frac{L^2 - h^2}{R_E^2 L}
\]

(6)

for a circular orbit of altitude \(h\), with \(R_E \approx 6378\) km being the earth’s radius.

Note that the model of atmospheric transmittance given by Eq. (6) is quite accurate for small zenith angles [36]. However, for space-based quantum communication at or near the horizon (i.e., for \(\zeta = \pm \pi/2\), more exact methods relying on the standard atmospheric model must be used \[87\]. In practice, it makes sense to set \(\eta_{\text{atm}} = 0\) at large zenith angles, effectively severing the quantum channel, because the loss will typically be too high for the link to be practically useful.

To summarize, the following parameters characterize the total loss \(\eta_{\text{bg}} = \eta_{\text{atm}} \eta_{\text{ts}}\): the initial beam waist \(w_0\), the receiving aperture radius \(r\), the wavelength \(\lambda\) of the satellite-to-ground signals, and the atmospheric transmittance \(\eta_{\text{atm}}\) at zenith. See Table I for the values that we take for these parameters.

Using the values in Table I, we plot in Fig. 3 (bottom) the total transmittance \(\eta_{\text{bg}}\) as a function of the ground distance \(d\) between two ground stations with a satellite at the midpoint; see Fig. 3 (top). We observe that for larger ground separations the total transmittance \(\eta_{\text{bg}}\) is actually larger for a higher altitude than for a lower altitude; for example, beyond approximately \(d = 1600\) km the transmittance for \(h = 1000\) km is larger than for \(h = 500\) km. We also observe that there are altitudes at which the transmittance is maximal. Intuitively, beyond the maximum point, the atmospheric contribution to the loss is less dominant, while below the maximum (i.e., for lower altitudes) the atmosphere is the dominant source of loss. This feature is unique for optical transmission from satellite to ground.

III. OPTIMAL NETWORK CONFIGURATIONS FOR GLOBAL COVERAGE

In order to successfully implement a global-scale satellite-based quantum internet, many factors must be taken into account, such as economics, current technology, resource availability, and performance requirements. Ideally, the most basic service that a satellite network should provide is continuous, on-demand entanglement distribution between two distant points on earth at a reasonably high rate. Given this performance constraint, important questions related to economics and resources arise, such as: How many satellites are needed for continuous global coverage? At what altitude should the satellites be placed? What entanglement-distribution rates are possible between any points on earth?

A. Description of the simulations and figures of merit

We address the questions put forward above by running several entanglement distribution simulations using the satellite network configuration described in Sec. II. We consider as our baseline requirement that a satellite network should provide continuous global coverage to two ground stations located on the equator. We separate the two ground stations by distances \(d\) between 100 km and 5000 km, and we run a 24-hour simulation with satellite configurations ranging from 20 to 400 satellites at altitudes between 500 km and 10000 km. A configuration is given by the number \(N_R\) of satellite rings and the number \(N_S\) of satellites per ring, as described in Sec. II. To our knowledge, this type of dynamic network simulation with satellites and two ground stations has not been previously studied. Our requirement of continuous coverage means that both ground stations must be simultaneously in view of a satellite at all times. We also impose an additional requirement that, even when in view of both ground stations, the total loss between a satellite and the ground station pair should not exceed 90 dB, in order to keep ebit rates above 1 Hz. Note that, based on the satellite constellations that we consider here, two ground stations at the equator are the worst case scenario, in the sense that two ground stations at higher or lower latitudes will always have greater satellite-to-ground loss on average (we show this in Fig. 5 below).

How do we evaluate the performance of our network? Since satellites are currently an expensive resource, we would like to have as few satellites as possible in the network while still maintaining complete and continuous coverage. We
could therefore take as our figure of merit the total number of satellites in the network. Specifically, given an altitude \( h \) of the satellites and distance \( d \) between the two ground stations, we define \( N_{\text{opt}}(h, d) \) to be the minimum total number of satellites needed to have continuous 24-hour coverage for the two ground stations. We could then minimize \( N_{\text{opt}}(h, d) \) over choices of altitudes and distances. On the other hand, loss is also an important consideration. We could thus take the quantity \( \eta_{\text{dB}}(h, d) \), which we define to be the average loss (in decibels) over a 24-hour period for a given altitude \( h \) and given distance \( d \), as our figure of merit and minimize it over \( h \) and \( d \). However, as one might expect, with fewer satellites the average loss would increase, thus decreasing entanglement-distribution rates, while increasing the number of satellites would decrease the loss. In order to balance our two competing goals — minimizing the total number of satellites and also minimizing the loss — we take as our figure of merit the product of \( N_{\text{opt}} \) and \( \eta_{\text{dB}}(h, d) \). Specifically, we take

\[
C(h, d) := N_{\text{opt}}(h, d)\eta_{\text{dB}}(h, d)
\]

In order to take into account the eventual decline in the real-world cost of satellites (as components on the satellite become miniaturized and the cost of launch (in dollars) goes down), we introduce a parameter \( \alpha \geq 1 \) that can be used to tune the extent to which the number of satellites dominates the cost function and that allows us to put more emphasis on having lower loss (thus higher ebit rates) than fewer satellites. Our modified cost function is then

\[
C_\alpha(h, d) := N_{\text{opt}}(h, d)\frac{\alpha}{\eta_{\text{dB}}(h, d)},
\]

and our goal is to take the satellite configuration (total number of satellites and satellite altitude \( h \)) that minimizes the cost function \( C_\alpha \) for a given value of \( \alpha \). In order to calculate \( N_{\text{opt}}(h, d) \) for given altitude \( h \) and separation \( d \), we perform a 24-hour simulation with a particular satellite configuration and determine whether there are any time gaps in coverage (times at which the pair of ground stations is not in view of a satellite). We repeat this for several satellite configurations and take the satellite configuration with the least total number of satellites such that there are no time gaps.

### B. Simulation results

The results of our simulations for \( d = 2500, 3500, 4500 \text{ km} \) are shown in Fig. 4. The complete set of results for all ground distances, satellite altitudes, and satellite configurations considered are contained in the data files accompanying the paper.

We first consider the quantity \( N_{\text{opt}}(h, d) \) as a function of altitude \( h \) for fixed ground-station separations \( d \). In terms of the satellite configurations, we find that at higher altitudes more satellites per ring are required in general, while at lower altitudes generally more rings are required. In terms of the total number of satellites, we find that as the altitude increases the total number of satellites decreases. Interestingly, however, as we continue to increase the altitude we find that there are altitudes (between 5000 km and 6000 km) at which the total number of satellites reaches a minimum. Beyond this range of altitudes, the required number of satellites increases. The presence of this minimum point gives us an indication of the altitudes at which satellites should be placed in order to minimize the total number of satellites. However, as shown in the bottom right panel of Fig. 4, for these altitudes the loss is generally quite high, around 80 dB.

Next, we consider the cost function in Eq. (8). We plot the normalized value

\[
\overline{C}_\alpha := \frac{C_\alpha}{C_\alpha^*} - 1,
\]

where \( C_\alpha^* = \min_{h,d} C_\alpha \), and the minimum is over the range of \( h \) and \( d \) as described in Sec. IIIA. For \( \alpha = 1 \), we find for all distances \( d \) that the minimum in the cost function corresponds to the minimum in \( N_{\text{opt}} \). Therefore, as expected, the number of satellites dominates our cost function for \( \alpha = 1 \) and leads to optimal altitudes and optimal satellite configurations with relatively high loss. To lessen the dominating effect of the number of satellites on the cost function, we let \( \alpha = 8 \) for the data shown in Fig. 4. Then, the location of the minimum shifts to a lower altitude, resulting in less loss but a larger total number of satellites.

Depending on the value of \( \alpha \) chosen, we can use the minimum of our cost function to decide on the number of satellites to put in our network (so that there is continuous coverage) and the altitude at which to put them — and thus determine the average satellite-to-ground transmission loss for the network. Alternatively, given a desired satellite-to-ground transmission loss, we can use our cost function to place a lower bound on the value of \( \alpha \), a lower bound on the minimum number of satellites needed for continuous coverage, and an upper bound on the altitude of the satellites. For example, from the table in Fig. 4, we see that in order to obtain a loss less than 73 dB at a ground distance separation of \( d = 2000 \text{ km} \), we would need \( \alpha > 8 \) and at least 40 satellites at an altitude less than 3000 km.
In the previous section, we obtained satellite network configurations that are optimal when considering the trade-off between total number of satellites and average loss over a 24-hour period. We also demanded in our simulations that there be no time gaps in coverage over the 24-hour period. Let us now test the performance of our optimal satellite configurations in terms of entanglement-distribution rates. Entanglement distribution is perhaps most relevant in the near term for entanglement-based quantum-key distribution (QKD) [2] and quantum teleportation [73]. Since the satellites in our network act as entanglement distribution sources, they need not be trusted. This allows for the execution of device-independent QKD protocols as well. For simplicity, we consider only single-mode satellite-to-ground transmission (no multiplexing) and photodetection only at the ground stations (i.e., no quantum memories). We mention that satellite-based QKD has also been analyzed in Refs. [68, 90, 91].

### IV. Entanglement-Distribution Rates

We start by looking at the rates for the simulations in Sec. III, in which two ground stations separated by a distance $d$ are placed on the equator. The results are shown in the left panel of Fig. 5. We assume that the satellites transmit entangled photon pairs at a rate of $R_{\text{source}} = 10^9$ ebits per second. For each point in the plot, the number of satellites is given by $N_{\text{opt}}(h, d)$. Qualitatively, the rates are consistent with the transmittances shown in Fig. 3. The highest rate among all distances is around $10^4$ ebits per second, which is obtained for a distance of $d = 1000$ km, an altitude of $h = 500$ km, and for $N_{\text{opt}}(h, d) = 225$ satellites ($N_R = 15$ rings and $N_S = 15$ satellites per ring).

In the right panel of Fig. 5, we display the results of simulating entanglement distribution when both ground stations are at a different latitude. Due to the fact that the satellites follow polar orbits in our network architecture, meaning...
FIG. 5. Entanglement-distribution rates for the simulations considered in Sec. III. In all cases, we assume that the satellites transmit entangled photon pairs at a rate of $R_{\text{source}} = 10^9$ ebits per second. (Left) Both ground stations at the equator. Each point corresponds to the optimal number $N_{\text{opt}}(h,d)$ of satellites, as defined in Sec. IIIA. (Right) Both ground stations at a higher latitude. The satellite constellation consists of $N_R = 15$ satellite rings with $N_S = 15$ satellites per ring.

that they congregate at the poles, the entanglement-distribution rates are higher for latitudes closer to the north and south poles than for the equator. This result also confirms that placing two ground stations at the equator is the worst-case scenario in terms of average loss (and thus average rate).

B. Rates for multiple ground stations

We now consider an example of entanglement distribution to multiple ground stations. We place 42 ground stations in a grid-like arrangement, with horizontal separation (i.e., separation in longitude) of approximately $18^\circ$ and vertical separation (i.e., separation in latitude) of approximately $18^\circ$. We use a satellite constellation of $N_R = 15$ rings and $N_S = 15$ satellites per ring, for a total of 225 satellites. In Fig. 6, we display the average loss for nearest neighbor pairs over a simulation time of 24 hours.

When performing our simulations, we find that at some times a satellite is in range of multiple ground station pairs. We anticipate that, in the near future, satellites will only have one entanglement source on board, so we impose the requirement that at any given time a satellite can distribute entanglement to only one ground-station pair. This requirement makes it necessary to uniquely assign a satellite to a ground-station pair at all times during the simulation. We assign a satellite to the ground-station pair that has the lowest loss among all ground-station pairs in range of that satellite. This type of assignment strategy means that, depending on the total number of satellites, there are times at which ground-station pairs do not receive any entangled photon pairs even though they are in range of a satellite (perhaps several), simply because the loss would be too high. More sophisticated time-sharing assignment strategies are possible, in which higher loss assignments are taken at certain times for the purpose of distributing entanglement to as many different ground-station pairs as possible. We do not consider such an assignment strategy here, except for when there is a ground-station pair that has only one satellite in view, but that satellite is in range of several other ground stations. In this case, we assign that satellite to the “lone” ground-station pair even if the loss is higher than another possible assignment of that satellite.

In the top plots of Fig. 6, we consider all possible nearest neighbor pairs in the simulation. As expected, the loss is lowest away from the equator (at a latitude of $0^\circ$), because neighboring ground stations are closer to each other away from the equator, due to the curvature of the earth and due to the nature of our satellite constellation (satellites congregate at the poles). We also find that diagonal nearest-neighbor pairs have higher losses compared to pairs that are horizontally or vertically separated. This can be explained by the fact that diagonally separated ground stations are farther away from each other than horizontally or vertically separated ground-station pairs. Our strategy for
assigning a satellite to a ground-station pair thus favors pairs that are horizontally or vertically separated. We also find that the maximum loss for a satellite altitude of \(h = 1000\) km is around 90 dB and the minimum loss is around 50 dB. For \(h = 5000\) km the maximum loss is around 105 dB and the minimum loss is around 75 dB.

In the bottom plots of Fig. 6, we simulate a network such that the satellites can only distribute entanglement to diagonally separated nearest-neighbor pairs. Now, since we do not allow entanglement distribution between horizontally and vertically separated pairs, we find that the maximum average loss decreases and the minimum average loss increases. We still find that ground-station pairs at latitudes farther away from the equator have lower loss.

In the central panels of Fig. 6, we plot average entanglement-distribution rates in a simple scenario without multimode transmission from the satellites and without multimode quantum memories at the ground stations. We assume that the satellites transmit entangled photon pairs at a rate of \(R_{\text{source}} = 10^9\) ebits per second. (Top) Entanglement distribution to all possible nearest-neighbor pairs. (Bottom) Entanglement distribution only to diagonal nearest-neighbor pairs.

### C. Entanglement distribution between major global cities

Although the ultimate goal is to have satellites distribute entanglement between any collection of nodes on the ground, an example of which we considered in the previous section, satellite-based quantum communication networks will likely have a hybrid form in the near term. In a hybrid network, the satellites distribute entanglement to major global cities, which act as hubs that then distribute entanglement to smaller nearby cities using ground-based links (see Fig. 1). With this in mind, we now consider entanglement distribution between pairs of major global cities. We run a 24-hour simulation with a satellite constellation of 400 satellites, with \(N_R = N_S = 20\), at altitudes of \(h = 500\) km,
### Table II.

| City pairs                  | Distance (km) | 500 km | 1000 km | 2000 km | 3000 km | 4000 km | 5000 km |
|----------------------------|---------------|--------|---------|---------|---------|---------|---------|
| Toronto – New York City    | 551           | 45.1   | 52.0    | 60.9    | 66.7    | 71.1    | 74.6    |
| Lijiang – Delingha        | 1200          | 50.6   | 52.9    | 60.5    | 66.3    | 70.7    | 74.3    |
| Houston – Washington DC    | 1922          | 75.1   | 66.9    | 73.7    | 78.3    | 81.1    | 83.1    |
| Sydney – Auckland         | 2156          | 65.5   | 59.3    | 62.9    | 67.6    | 71.6    | 74.9    |
| New York City – London     | 5569          | > 90   | > 90    | > 90    | > 90    | > 90    | > 90    |
| Singapore – Sydney         | 6306          | > 90   | > 90    | > 90    | > 90    | > 90    | > 90    |
| London – Mumbai            | 7191          | > 90   | > 90    | > 90    | > 90    | > 90    | > 90    |

Average loss over a 24-hour period between select pairs of major global cities for a constellation of 400 satellites ($N_R = N_S = 20$) at various altitudes. The following cities are included in the simulation: Toronto, New York City, London, Singapore, Sydney, Auckland, Rio de Janeiro, Baton Rouge, Mumbai, Johannesburg, Washington DC, Lijiang, Ngari, Delingha, Nanshan, Xinglong, and Houston.

1000 km, 2000 km, 3000 km, 4000 km, and 5000 km. We include the following cities in the simulation: Toronto, New York City, London, Singapore, Sydney, Auckland, Rio de Janeiro, Baton Rouge, Mumbai, Johannesburg, Washington DC, Lijiang, Ngari, Delingha, Nanshan, Xinglong, and Houston. The Lijiang-Delingha pair was chosen for comparison to current experiment [70]. The simulation results are shown in Table II. We use the same strategy as in Sec. IVB to uniquely assign satellites to ground-station pairs.

From Table II, we see that at around a distance of 6300 km, which is the distance between Singapore and Sydney, we can only obtain an average loss less than 90 dB for altitudes greater than 2000 km. Similarly, entanglement distribution between London and Mumbai (which are 7200 km apart) at an average loss less than 90 dB is possible only for an altitude greater than 3000 km. These results suggest that, using our constellation of 400 satellites, a distance of around 7500 km is the highest for which entanglement distribution at a loss less than 90 dB can be achieved. Indeed, for Houston and London (which are 7800 km apart), we find that the average loss is greater than 90 dB for all of the satellite altitudes that we consider.

**D. Comparison to ground-based entanglement distribution**

Let us now compare the entanglement-distribution rates obtained with satellites to the rates that can be obtained via ground-based photon transmission through optical fiber with the assistance of quantum repeaters. In particular, we compare the rates in Sec. IVA for two ground stations at the equator separated by a distance $d \in [100, 2000]$ to ground-based repeater chains with endpoints the same distance $d$ apart. For the latter, we suppose that the distance $d$ between the endpoints is split into $M$ elementary links by $(M - 1)$ equally spaced quantum repeaters. We place a source at the center of each elementary link that transmits entangled photon pairs to the nodes at the ends of the elementary link at a rate of $R_{\text{source}} = 10^{9}$ ebits per second. We assume that the probability of establishing an elementary link is $p = e^{-\alpha d}$, where $\alpha = \frac{1}{22 \text{ km}}$ [85]. Under these conditions, we can apply the general result in Ref. [92, Theorem 1] (see also Ref. [93]) to conclude that the rate $R_M$ (in ebits per second) of entanglement distribution between the endpoints is bounded from above as follows:

$$R_M \leq \frac{R_{\text{source}}}{2} \left( \sum_{k=1}^{M} \frac{(-1)^{k+1}}{k} \frac{(1-p)^k}{1-(1-p)} \right)^{-1}.$$  \hspace{1cm} (10)

Note that our assumption that $p = e^{-\alpha d}$ is the best-case scenario in which the sources fire perfect Bell pairs and the Bell measurements for entanglement swapping are deterministic. Furthermore, the upper bound in (10) holds in the case that the quantum repeaters have perfect read-write efficiency and have infinite coherence time. The right-hand side of Eq. (10) is therefore the best rate that can be achieved in a repeater chain with probabilistic links operating in a repeat-until-success fashion.

In Fig. 7, we compare the rate on the right-hand side of Eq. 10 with the rates shown in the left panel of Fig. 5. Remarkably, for an altitude of 500 km, the satellite-based entanglement distribution scheme outperforms the ground-based scheme by a significant margin for all distances up to at least 2000 km, even when considering a repeater chain with $M = 50$ elementary links. For higher altitudes, we find that there are critical distances beyond which satellites...
FIG. 7. Satellite-based entanglement-distribution rates for two ground stations separated by a distance $d$ on the equator (identical to those presented in left panel of Fig. 5) compared to the optimal rate (as given by the right-hand side of (10)) of a ground-based repeater chain of the same distance $d$ consisting of $M$ elementary links of equal length.

outperform ground-based repeater schemes. For example, for an altitude of 1000 km, the satellite-based scheme outperforms the $M = 50$ ground-based scheme beyond 250 km. On the other hand, we find that at an altitude of 4000 km the ground based scheme with $M = 50$ repeaters outperforms the satellite-based scheme up to around 2000 km. We emphasize, however, that the ground-based rates are for memories with infinite coherence time, while the satellite rates do not involve quantum memories. We thus find that satellites offer a significant advantage over ground-based entanglement distribution, especially because ground-based schemes offer an advantage only when the number of repeaters is quite high and when they have very high coherence time. Currently, quantum repeaters exist mostly in a laboratory environment and are not at the stage of development that they can be widely deployed in the field, and they certainly do not have high enough coherence times to achieve the rates presented here.

V. CONCLUSIONS

In this paper, we explored the possibility of using satellites for a global-scale quantum communications network. Our network architecture consists of a constellation of satellites in polar orbits around the earth that transmit entangled photon pairs to ground stations (see Sec. II). By defining in Sec. III a figure of merit that takes into account both the real-world cost of satellites as well as the satellite-to-ground transmission loss, we provided estimates on the number of satellites needed to maintain full 24-hour coverage at a high rate based on the minimum value of the figure of merit. Using our figure of merit to decide the number of satellites in the network, in Sec. IV we estimated the transmission loss and entanglement-distribution rates that can be achieved for two ground stations placed at various latitudes, for multiple ground stations at various locations in a grid-like arrangement, and for multiple major global cities in a hybrid satellite- and ground-based network in which the cities act as hubs that receive entanglement from satellites and disperse it to surrounding locations via ground-based links. In Sec. IV D, we compared the rates for two ground stations using satellites to the rates obtained using ground-based links with quantum repeaters. Even in the best-case scenario for the ground-based scheme, in which there are several quantum repeaters in a chain, each with infinite coherence time, the satellite-based scheme achieves significantly higher rates over longer distances without the need for any quantum-repeaters. For such distances, our results suggest that a satellite-based global quantum internet will remain the preferred option over ground-based repeater schemes into the future, especially with the improving miniaturization and increasing fidelity of entanglement distribution sources [64, 81] and the decreasing cost and miniaturization of satellites [50, 52, 53].

In summary, the broad-scope vision is to have a quantum-connected world, similar to today’s internet, where users across the globe can share quantum information for any desirable task. In our view, the backbone of such a network is built on local and global quantum entanglement, in which intercontinentally separated ground stations located in major cities act as entanglement hubs connecting the local network users of one city to those of another (Fig. 1). Hybrid networks interfacing space-based quantum communication platforms with ground-based quantum repeaters will make this vision a real possibility.
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