

How far can one send a photon?

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The answer to the question *How far can one send a photon?* depends heavily on what one means by a *photon* and on what one intends to do with that photon. For direct quantum communication, the limit is approximately 500 km. For terrestrial quantum communication, near-future technologies based on quantum teleportation and quantum memories will soon enable quantum repeaters that will turn the development of a world-wide-quantum-web (WWQW) into a highly non-trivial engineering problem. For Device-Independent Quantum Information Processing, near-future qubit amplifiers (i.e., probabilistic heralded amplification of the probability amplitude of the presence of photonic qubits) will soon allow demonstrations over a few tens of kilometers.

Keywords quantum communication

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rephrased again. *How far can one send a photon on Earth using present-day, or near-future, technologies?* Again, the answer depends on other factors.

In classical optical communications, light pulses are routinely transmitted across oceans, e.g., from France to the US over a single and continuous optical fiber approximately 5000 km in length. In this scenario, do photons propagate across the entire Atlantic? Assuming a mean loss of 0.2 dB/km, the total loss is 1000 dB, i.e., a transmission of 10^{-100} . Thus, even if the initial light pulse contains millions of photons (for example, 1 ns of a mW, i.e., 10^{-12} J, hence approximately 10^7 photons), there is a negligible chance that a photon from the initial pulse will be successfully transmitted from France to the US. However, classical optical communication functions well: approximately every 50 km, when only 10% of the photons remain, a laser mechanism amplifies the light pulse back to its initial state, while introducing some unavoidable-but-tolerable noise. This is very efficient and effective. It is probably not correct to state that some photons make the entire journey, although this depends on one's definition of a photon. If one thinks of a photon produced by stimulated emission as a new photon, then the chance that any photon leaving France will arrive in the US is vanishingly small. However, photons are excitations of an optical mode (e.g., the single mode of optical fibers); hence, the question is not well defined, and must be made more precise. *How far can one send a bit of information encoded in a single photon, on Earth,*

1 Introduction

How far can one send a photon? In the future, it will be possible to store a photon in a quantum memory and transport it by airplane to the other side of the Earth. However, this is a distant future vision; hence, the question must be rephrased. *How far can one send a photon with present-day, or near-future, technologies?* The answer depends on other factors. There will soon be quantum communications between low-orbit satellites and Earth, i.e., over several hundreds of kilometers. Furthermore, if one observes light from distant stars or galaxies, then one is analyzing photons that have traveled astronomical distances. However, analyzing the question in this manner is somewhat inaccurate, because we did not send those photons. Thus, the question should be

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using present-day, or near-future, technologies? This excludes classical optical communication, as a bit encoded in a single-photon will be lost when the photon passes through a classical amplifier.

2 Direct quantum communication

On Earth, the best communication channel is, undoubtedly, an optical fiber. At present, the best fibers have losses close to 0.16 dB/km. Hence, an optimistic loss for near-future fibers is approximately 0.15 dB/km – the probability that a photon makes it through 500 km is thus $10^{-7.5}$. This is low, but not unreasonably low. Indeed, if the rate at the transmitter is approximately 10 GHz, then, on average, approximately one hundred photons arrive at the receiver every second. Moreover, at present there are single-photon detectors at telecom wavelengths (i.e., compatible with the highest transmission coefficient of telecom optical fibers) with nearly 100% efficiency and remarkably low dark counts [1]. To the best of my knowledge, the longest distance that single-photons, or more precisely, pseudo-single-photons (i.e., weak pulses with less than one photon per pulse) have been sent and detected is 307 km; this was achieved at a recent QKD demonstration by my colleague Zbinden's group over ultra-low-loss fibers from Corning, operating at a source clock rate close to 1 GHz [2]. However, the difference between 300 and 500 km is significant, because the transmission probability per photon decreases exponentially. Consequently, 500 km is still out of reach. At best, one could aim for 100 GHz sources, i.e., a gain of 20 dB, improve the detectors from 20% (as in Ref. [2]) to 100% (+7 dB), lower the fiber loss from 0.16 dB/km down to 0.15 dB/km (a gain of +3 dB over the 300 km), and use true single-photons instead of the 0.5 photon per pulse (+3 dB). Unfortunately, there exist no further straightforward improvements. Hence, there is a total potential gain of 33 dB, corresponding to an additional length of $33/0.15=220$ km for a total distance just above 500 km [3]. I would be truly surprised if anyone demonstrates a longer distance during my lifetime (which I consider as the near future).

The likelihood of improving photon transmission distances depends on various factors. First, it depends on the minimal rate, which might be a few tens of bits per second. More interestingly, there are actually at least two intriguing possibilities to overcome the direct quantum communication upper bound of 500 km: heralded probabilistic amplification of photonic qubits, and quantum repeaters.

3 Quantum repeaters

Let us first analyze the second possibility, i.e., quantum repeaters [4]. The basic ingredient is quantum teleportation; this remarkable process exploits entanglement as a quantum communication channel [5, 6]. Once two qubits are entangled, this can be used to teleport the quantum state of a third qubit from one side to the other, independently of the distance separating the two entangled qubits. Assume all three qubits are photonic qubits, e.g., polarization qubits or time-bin qubits [7, 8]. Because the receiving qubit and photon are indistinguishable from the initial qubit and photon, one may argue that this corresponds to sending one photon from the location of the initial qubit all the way to the receiver. However, through which trajectory? In quantum teleportation there is no trajectory, nothing in our 3-dimensional space (it all occurs in Hilbert space). Thus, if one chooses to include this process in our list of answers to our basic question *How far can one send a photon?*, then it could be argued that the straight line determines the relevant distance. Accordingly, if a photonic qubit is teleported from Europe to Australia, the distance is not half the Earth's circumference, but its diameter. However, this would not satisfactorily address the scientific and technological challenges. Indeed, before teleporting anything, the two end points must be entangled; this is performed by first defining a trajectory relating the end points and subsequently dividing it into many relatively short sections. Note that this is a bit similar to classical optical communication's use of laser mechanisms to re-amplify the optical signal approximately every 50 km, as discussed above. Moreover, the question whether the photon at the end point is the same as the initial one is also a bit similar. Thus, the very process by which quantum teleportation over long terrestrial distances will someday be realized defines a natural notion of distance.

As shown in Fig. 1, the long distance is now divided into numerous sections. Note that if one works in series, that is, first teleport a qubit from the first point to the second, then from the second to the third, and so on until the final receiving point, the process would be exponentially inefficient for the total distance. Indeed, one would first need to entangle the first point with the second point and perform a first teleportation, and then entangle the second point with a third point and perform a second teleportation, and so on. However, entangling two points requires sending photons between these two points (either from a middle station to both points, or from one point to the other); this is as inefficient as directly sending the photon carrying the qubit [3].

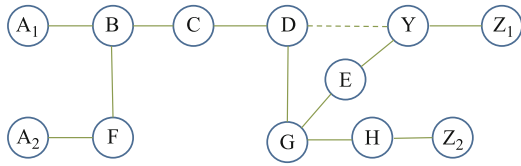


Fig. 1 Example of a small quantum network with nodes $A_j, B, \dots, Y, Z_j, j = 1, 2$. Nodes B, \dots, Y must hold as many quantum memories as there are links to that node. Each link exploits quantum teleportation.

Hence, operating in series is not more efficient than direct communication (it is actually much less efficient because of the many teleportation processes). One needs to operate in parallel, attempting to entangle every pair of nearby nodes at the same time. However, again, the probability that all these entanglement distributions will work simultaneously is exponentially inefficient. Hence, the only means to exploit teleportation to improve the overall efficiency is to assume that some pairs of nearby points will be entangled before others, and wait for the others.

However, how can one say to a photon *Please, wait a while?* In this case, synchronization is required, and can be performed using quantum memories. In summary, without quantum memories, there is no quantum repeater.

Moreover, the quantum memories must have some further quality. Ideally, one should be able to send in a photon (write) and release it (read) on demand and know when the memory is loaded, i.e., when the qubit is stored. Actually, the exact requirements are subtle and depend on the exact protocol; we will not pursue this discussion here (and it is likely that the optimal protocol has not yet been invented). It must be emphasized that presently, somewhat surprisingly, the best known protocol does not use photon pairs, but uses single-photons [9].

There are at least five specifications for quantum memories that are crucial, and independent of any protocol:

- 1) Efficiency, that is the probability that an incoming photon is properly released at the appropriate time. Note that inefficiency is equivalent to additional loss.
- 2) Fidelity, i.e., the overlap between the states of the in-qubit and the out-qubit should be close to one. This is a much discussed parameter, but in practice, photons that are not lost have a very high fidelity. Hence, thanks to the natural post-selection of photons that make it to the detector, quantum commu-

nication with discrete variables has some built-in error filtering.

- 3) Memory time, which determines the size of the quantum network that can be synchronized. At first, only synchronization between nearby points is required; however, once next neighbors are entangled, synchronization over longer and longer distances is required. Hence, the quantum memory time defines the longest distance, and our question becomes *How long can one hold a photonic qubit in a quantum memory?* In practice, a factor of ten should be added as a margin to allow time to repeat the entanglement distribution process many times, until success is achieved. Today, the longest time for read-write quantum memories is only approximately one millisecond¹⁾ [12, 13], which is insufficient to surpass direct communication. However, steady progress allows one to be optimistic. For single-photon read-write quantum memories, one-second storage times are on the horizon. Recall that *storage time* is defined as the exponential decay time of the memory efficiency. Further, recall that for single-photon memories, those photons that come out of the memory do so with high fidelities, in particular, with fidelities above the optimal cloning threshold.
- 4) There is a fourth very important specification: bandwidth. Indeed, quantum memories that are useful for quantum communication should be able to store photons with a bandwidth of at least tens of MHz. A few GHz would be better. At present, the best quantum memory from this point of view has been demonstrated in Calgary, Canada [14].
- 5) A final specification required for quantum memories as building blocks for quantum repeaters is the ability to store multiple photonic qubits, multiplexed either in time [15], space, or frequency [16]. Indeed, once a memory has been used, i.e., it stores a qubit, one must wait for information from other nodes in the network before either releasing the qubit or cleaning out the quantum memory, such that it is again ready for a fresh qubit. Moreover, this communication time multiplied by the success probability of some entanglement distribution or some Bell-state measurement can be rather large. Accordingly, without a multimode capacity, a quantum memory would not be able to make large quantum networks realistic [17].

¹⁾There are quantum memories with longer storage times; however, they do not allow incoming photons to be stored. They either generate photons that are entangled with the quantum memory (hence, there are no read-write quantum memories, but read-only memories [32]), or they do not have any input-output [32].

4 Heralded amplifier

Let us now analyze the other possible method of overcoming the 500 km hard limit for direct long-distance quantum communication mentioned above. It is possible to, in essence, “amplify” a photon [18]. This fact is, by itself, surprising and fascinating, and deserves to be researched by physicists. There is no contradiction with the no-cloning theorem, because what gets amplified is only the probability amplitude that the photon is not lost. Furthermore, the process is probabilistic, that is, it does not work each time. However, when it does work, there is a heralding signal.

Imagine a box with an incoming and outgoing optical fiber, as shown in Fig. 2. There is also a synchronization electronic input that provides the box with the times at which it may expect a photon. At those times, there is some probability that an electronic signal heralds the presence of a photon in the outgoing fiber. More precisely, the signal heralds that there is a large chance that a photon is present in the outgoing fiber — a photon identical to the one that was expected in the incoming fiber. Clearly, such a box is useful only if the chance of there being an outgoing photon, when the heralding signal is on, is larger than the chance that there was an incoming photon. Finally, if that initial photon carried a qubit (e.g., in polarization or a time-bin qubit), then the outgoing photon would carry the same qubit.

A brief explanation of how such a box functions is provided below; however, we must first consider whether such a “photon-amplifier” box facilitates the sending of photons over long distances. Clearly, it depends. However, in this case, it depends on the photon’s intended use. If the purpose is merely to detect the photon at the receiving side, then “photon-amplifiers” are of no use. However, in modern quantum communication, there is another task in which it must be known, with fairly high probability, that a photon is arriving before choosing in which basis to measure it.

This task is called Device-Independent Quantum In-

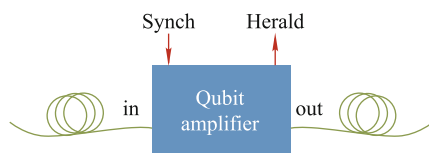


Fig. 2 A qubit amplifier is a box that has an input optical fiber “in” and an output fiber “out”, a synchronization electronic input, and an electronic heralding signal. The synchronization signal informs the box that there is a chance that a photonic qubit will arrive at the input fiber. Occasionally, the heralding signal informs the user that there is a larger probability that the photonic qubit is present at the output fiber.

formation Processing (DIQIP), a truly remarkable sub-field of Quantum Information Science. DIQIP is based on the fact that some quantum correlations cannot be mimicked by pre-established shared randomness and local processing [19]. Such correlations are called non-local and violate some Bell inequalities [20, 21]. They gave rise to heated debates, first between the founding fathers of quantum theory, and then between the vast majority of physicists from the “shut up and calculate” school and the small community of physicists and philosophers interested in the foundation of quantum physics. However, at present, these non-local correlations are recognized as a resource for performing seemingly impossible tasks. Intuitively, the power of non-local correlation stems from the mere fact that if no local variables can mimic them, then neither can an adversary. It should be emphasized how remarkable this is: the mere observation that some correlation violates some Bell inequality suffices to guarantee that this correlation contains privacy [22], whether it is private randomness or a cryptographic key (i.e., private randomness shared between several partners). There is no need for the quantum formalism, Hilbert spaces, self-adjoint operators, or state-vectors: the mere observation of the correlation suffices: this is pure “quantum magic” (it is quantum because, according to present-day physics, only quantum theory predicts the existence of non-local correlations). However, for this to work, all trials must be taken into account, including those in which the photon never arrived at the receiver. Indeed, if too many photons are missed, then the correlation between the remaining photons can be mimicked by local variables: local variables (plus local processing) can take advantage of the possibility to mimic lost photons. The precise threshold on the ratio of photons that must be detected for DIQIP to be possible is still not completely known, but it is known that it must be relatively high — somewhere between 70% and 90% [19, 20].

I believe that *photon amplifiers* will be used in the first demonstrations of DIQIP over tens of kilometers. The question then becomes, how far can one go with photon-amplifiers? With perfect photon-amplifiers, distances can be achieved that are similar to those of single-photons, i.e., about 500 km without quantum repeaters. Indeed, if one can detect one photon per second, then one can also amplify all the photon probability amplitudes, and an ideal photon-amplifier box will herald one success every two seconds (the factor of two comes from the four Bell-state measurement outcomes, of which only two amplify the photon; the other two cannot be used).

The following section explains how photon-amplifiers work in more detail, with an explanation based on quantum teleportation with partial entanglement. For

this purpose, we compute what occurs when a qubit $\psi = c|0\rangle + s|1\rangle$ (where we assume c real and s complex with $c^2 + |s|^2 = 1$) is teleported using a partially entangled state $\Phi_{pe} = t|0, 1\rangle + ir|1, 0\rangle$, with t and r real and $t^2 + r^2 = 1$. The form of Φ_{pe} is chosen to be easily realizable with single-photons and a mere beam-splitter as described below, but at this time, the discussion will be kept abstract. Let us expand $\psi \otimes \Phi_{pe}$ in the Bell basis for the first two qubits with $\phi^\pm = (|00\rangle \pm i|11\rangle)/\sqrt{2}$ and $\psi^\pm = (i|01\rangle \pm |10\rangle)/\sqrt{2}$ (note the unusual phases i that we chose for later convenience):

$$\begin{aligned} \psi \otimes \Phi_{pe} &= \frac{1}{2}\phi^+ \otimes (sr|0\rangle + ct|1\rangle) \\ &+ \frac{1}{2}\phi^- \otimes (-sr|0\rangle + ct|1\rangle) \\ &+ \frac{1}{2}\psi^+ \otimes (cr|0\rangle + st|1\rangle) \\ &+ \frac{1}{2}\psi^- \otimes (cr|0\rangle - st|1\rangle) \\ &= ct|001\rangle \\ &+ isr|110\rangle \\ &+ \frac{1}{2}\psi^+ \otimes (cr|0\rangle + st|1\rangle) \\ &+ \frac{1}{2}\psi^- \otimes (cr|0\rangle - st|1\rangle). \end{aligned} \tag{1}$$

Let us first concentrate on the case of a Bell-state measurement result ψ^+ (third line in Eq. (1)). In this case, the teleported qubit state reads $cr|0\rangle + st|1\rangle$, which, after the normalization that corresponds to the probability of that result, equals $\sqrt{1 - |s|^2g^2}|0\rangle + sg|1\rangle$ with a “gain” factor

$$g = \frac{t}{\sqrt{c^2r^2 + |s|^2t^2}}. \tag{3}$$

Figure 3 illustrates the deformation of the Poincaré sphere due to this gain. Note that the gain g depends on the initial state through c and s , and that $g \leq |s|^2$, indicating that the probability amplitude of $|0\rangle$ is still real. It is worth rewriting this in terms of the mean value of the z -component, $\eta = \langle \psi | \sigma_z | \psi \rangle$:

$$\eta \rightarrow \frac{\eta + (2t^2 - 1)}{1 + \eta(2t^2 - 1)}. \tag{4}$$

This expression is identical to the addition of two polarization dependent losses [23], and the addition of velocities in special relativity, because in all cases the quantities to be “added” are bounded from below and above.

A priori, this does not appear useful, but consider the basic qubit states $|0\rangle$ and $|1\rangle$ as Fock photon number states, i.e., vacuum and single-photon states, respectively. Then, the deformation corresponds to an increase

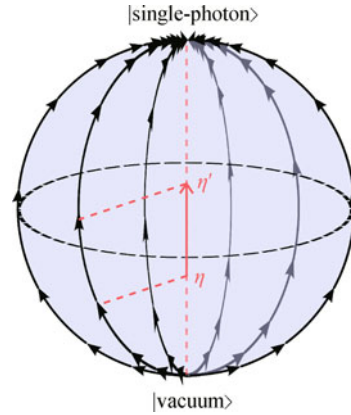


Fig. 3 Deformation of the Poincaré sphere in a photon amplifier. Each point of the sphere is mapped to another point on the sphere (e.g., pure states to pure states), but higher on the z -axis, i.e., closer to the single-photon state. The points on the z -axis move straight up; other points inside the sphere follow more complex trajectories.

of the probability amplitude of the single-photon state by the gain factor g . Note that when $t = \sqrt{1/2}$, $g = 1$, corresponding to standard quantum teleportation with a maximally entangled state. However, for $t > \sqrt{1/2}$, the gain is larger than 1, i.e., when the heralding signal is on, the probability of an outgoing photon is larger than the probability of an incoming photon; thus, we have “amplified the photon.”

Whenever the Bell-state measurement result is ψ^- , the analysis is identical, with the same gain factor, except that state $|1\rangle$ receives a π phase shift, as seen in the last line of Eq. (1). The two other Bell-state measurement results, $|\phi^\pm\rangle$, corresponding to the first two lines of Eq. (1) are also interesting; however, we will not analyze them here, because the phases of the vacuum and single-photon are swapped. Hence, only two of the four Bell-state measurement results are relevant.

Note that in practice, one uses threshold single-photon detectors that do not distinguish cases with one or more photons. Equation (2) shows what occurs: the first line corresponds to a result that should never occur (except when caused by dark counts), as there are no photons arriving on the heralding detectors. The second line should be eliminated using Photon Number Resolving (PNR) detectors; however, with non-PNR detectors, this results in a heralding vacuum probability that is unacceptably large. For this reason, when using non-PNR detectors, the exact threshold value for t (i.e., the value above which amplification occurs) depends on the input state; see [24, 25].

Thus far, we have only considered “photon amplifiers.” However, one is truly interested in “qubit amplifiers”, i.e., devices that amplify the probability amplitude that

a photonic qubit (e.g., a polarization or time-bin qubit) is increased. Because the photon amplifier is a coherent quantum process, it can straightforwardly be generalized to qubit amplification by merely first separating the two (polarization or time-bin) modes, then amplifying each mode, and finally recombining the two modes [26–28].

Let us emphasize that in teleportation, entanglement is always used twice; the first time as a “quantum teleportation channel” and the second time as Bell-state measurement results. This second usage of entanglement for the joint measurement of two systems, typically two qubits, has received significantly less attention than entanglement as joint states of distant systems. In particular, we have no abstract model for it, contrary to entangled states whose abstract essence is captured by the so-called non-local box of Popescu and Rohrlich [29].

In summary, qubit amplifiers allow one to increase the probability amplitude of the presence of photonic qubits. The process is probabilistic, but comes with an electronic signal that heralds successful processes. The success probability is, at most, the probability of the presence of a photon in the input port. Hence, this process cannot allow the rate of quantum channels to be increased; rather, the opposite is true, because the success rate of the amplifier is usually quite low. However, it offers significant advantages for DIQIP applications in which one knows with high confidence when a photon is present; hence, one knows when to ask questions of the photon. This is crucial for proper violations of Bell’s

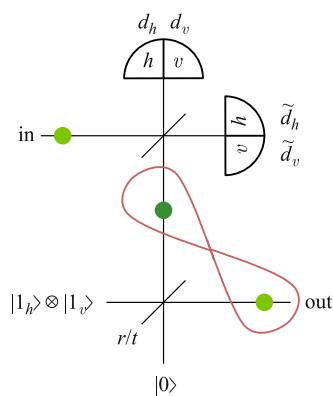


Fig. 4 A qubit amplifier implementation must contain two single-photon sources, one in state $|1_h\rangle$ and the other in state $|1_v\rangle$, for horizontal and vertical polarization. Each photon passes through an imbalanced beam-splitter with transmission t such that each of the two photons produces a partially entangled state. The reflected mode meets the in-photonic qubit on a 50%–50% beam splitter, followed by two detectors that herald successful amplification. Each detector distinguishes V and H polarized photons. Ideally, these detectors should be Photon Number Resolving (PNR), such that state ϕ^\pm can be discriminated and disregarded. In practice, however, standard non-PNR detectors can be used, as in the interesting case in which the probabilities of ϕ^\pm are very low (the probability of an in-photon $|s|^2$ is very low).

inequality, because each instance in which Alice and Bob ask a question of their qubit must be counted in the statistical analysis.

At present, there are very few experimental demonstrations of qubit amplifiers [30, 31]. However, the result in Ref. [31] allows optimism for the realization of an all-fiber practical photonic qubit amplifier at telecom wavelengths. Still, there is ample opportunity for substantial progress.

Finally, Fig. 4 and the caption present the inside of a qubit amplifier.

5 Conclusion

In summary,

- 1) Photons can travel over astronomical distances despite the enormous losses that occur during transmission, as it suffices to send correspondingly enormously large numbers of photons to guarantee that, statistically, at least some complete the entire journey.
- 2) On Earth, optical signals can be sent all around the world thanks to stimulated emission. However, no “individual” photon (whatever that means) makes the entire journey.
- 3) Direct communication of a bit of information, encoded in a single-photon, is limited to approximately 500 km, even in the best optical fibers.
- 4) Quantum repeaters allow this limit to be overcome, in principle. However, the question then becomes *For how long can one store a photonic qubit in a quantum memory?* Roughly, the distance is given by the memory time multiplied by the speed of light. This should soon approach one second for read-write quantum memories.
- 5) Heralded probabilistic photon amplifiers (that amplify the probability amplitude of the photon’s presence) are useful for extending quantum communication to Device-Independent applications, i.e., to applications that require the receiver to know when there is a large chance that a photon is present before choosing in which basis to measure it.

Quantum communication all over our planet is a not-too-distant goal. Quantum repeaters and high-fidelity quantum teleportation will make this possible, although the engineering challenges are still formidable.

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32. There are quantum memories with longer storage times; however, they do not allow incoming photons to be stored. They either generate photons that are entangled with the quantum memory (hence, there are no read-write quantum memories, but read-only memories [10]), or they do not have any input-output [11].