Entanglement distribution over a 96-km-long submarine optical fiber

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Quantum entanglement is one of the most extraordinary effects in quantum physics, with many applications in the emerging field of quantum information science. In particular, it provides the foundation for quantum key distribution (QKD), which promises a conceptual leap in information security. Entanglement-based QKD holds great promise for future applications owing to the possibility of device-independent security and the potential of establishing global-scale quantum repeater networks. While other approaches to QKD have already reached the level of maturity required for operation in absence of typical laboratory infrastructure, comparable field demonstrations of entanglement-based QKD have not been performed so far. Here, we report on the successful distribution of polarization-entangled photon pairs between Malta and Sicily over 96 km of submarine optical telecommunications fiber. We observe around 257 photon pairs per second, with a polarization visibility above 90%. Our results show that QKD based on polarization entanglement is now indeed viable in long-distance fiber links. This field demonstration marks the longest-distance distribution of entanglement in a deployed telecommunications network and demonstrates an international submarine quantum communication channel. This opens up myriad possibilities for future experiments and technological applications using existing infrastructure.

Significance

Entanglement, the existence of correlations in distant systems stronger than those allowed by classical physics, is one of the most astonishing features of quantum physics. By distributing entangled photon pairs over a 96-km-long submarine fiber, which is part of existing infrastructure carrying internet traffic, we demonstrate that polarization entanglement-based quantum key distribution (QKD) can be implemented in real-world scenarios. QKD facilitates secure communication links between two parties, whereby the security is guaranteed by the basic property of quantum mechanics that the quantum state of a photon cannot be duplicated.

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Content may be added.
A source of polarization-entangled photon pairs was located in Malta in the central data center of one of the local telecommunications providers (Melita Ltd.), close to Fort Madliena. One photon from each pair was sent to a polarization analysis and detection module located in Malta close to the source. This module consisted of a half-wave plate and a polarizing beam splitter with single-photon detectors connected to the transmitted and reflected output ports. The entangled partner photon was sent to Sicily via a 96-km-long submarine telecommunications optical fiber cable, which introduced an attenuation of about 22 dB. The link consists of several International Telecommunication Union (ITU) Telecommunication Standardization Sector G.655 compliant fibers, some of which were actively transmitting internet traffic in the C band around 1,550 nm. Two dark fibers within the same cable represented the quantum channel and a synchronization channel used to establish a common timing reference between time-tagging modules by an intensity-modulated diode laser. In Sicily, the fiber link was accessed through an underground utility vault on the outskirts of the town of Pozzallo. The fiber link was connected to a mobile polarization detection module installed in a stationary van and driven to the site each day.

The entangled photon source was based on spontaneous parametric down-conversion (SPDC) in a periodically poled type 0 lithium niobate (MgO:ppLN) crystal (Materials and Methods has details). The crystal was pumped from two directions within a Sagnac loop. The emitted down-converted photons were separated from the pump beam by a dichroic mirror. The source produced polarization-entangled signal and idler photons in the two-photon Bell state

\[
|\Phi\rangle = \frac{1}{\sqrt{2}} (|V_{\lambda_{s}}V_{\lambda_{i}}\rangle - |H_{\lambda_{s}}H_{\lambda_{i}}\rangle),
\]

where we denote the signal (idler) wavelength by \(\lambda_{s}\) (\(\lambda_{i}\)) and the polarization degree of freedom by horizontal (H) or vertical (V). Exploiting energy conservation in the SPDC process, the signal and idler photons were emitted with an equal spectral distance of the channels from the central wavelength of 1,550.15 nm. Following the terminology of the ITU, we chose the wavelength division multiplexing (WDM) channel 36 (\(\lambda_{s} = 1,548.52\) nm) for the signal photons to be sent to Sicily, while the idler photons in channel 32 (\(\lambda_{i} = 1,551.72\) nm) were detected locally in Malta. Superconducting nanowire single-photon detectors (SNSPDs) were used for the detection of the photons in Malta, while in Sicily, the detection system was more mobile and used single-photon avalanche detectors (SPADs) (Materials and Methods has more details on the detection system).

A signal generator located in Malta triggered a local time-tagging unit and modulated the intensity of a 1,550-nm laser, which synchronized the time-tagging unit in Sicily over a separate fiber. Each detection event was recorded by the respective time tagger and written to computer files locally and independently in Malta and Sicily. The two-photon coincidence events were identified by performing a cross-correlation between the photon detection times (Fig. 2), which can also be understood as a histogram of detection time delays.

**Results**

First, to quantify the quality of the entangled state after transmission through the submarine fiber, we performed a series of two-photon correlation measurements. In Sicily, the polarization analyzer was set to measure in either the H/V or diagonal (D)/antidiagonal (A) basis. The polarization angle \(\phi_{M}\) analyzed in Malta was scanned from 0° to 360° in steps of 20°. For each angle setting in Malta, we accumulated data for a total of 60 s. The best-fit functions to the experimental data, two of which are shown in Fig. 3, exhibit a visibility of 86.8 ± 0.8%
in the H/V basis and 94.1 ± 0.2% in the D/A basis. Second, to further quantify the quality of polarization entanglement, we combined the results of the coincidence scans to yield the Clauser–Horne–Shimony–Holt (CHSH) quantity $S(\phi_M)$, which is bounded between −2 and 2 for local realistic theories but may exceed these bounds up to an absolute value of $2\sqrt{2}$ in quantum mechanics (36). To mitigate against systematic errors due to misalignment of the polarization reference frames, we used a best fit to the coincidence data (e.g., as shown in Fig. 3) to compute $S(\phi_M)$ as shown in Fig. 4. We observed the maximum Bell violation for a CHSH value of $-2.534 \pm 0.08$, which corresponds to $\sim 90\%$ of the Tsirelson bound (37) and is in good agreement with the visibility of the two-photon coincidence data. Note that this value was obtained for $\phi_M = 63.5^\circ$, which corresponds to an offset of $4.0^\circ$ from the theoretical optimum ($67.5^\circ$). We ascribe this difference to a residual error in setting the zero point of our wave plates and imperfect compensation of the birefringence of the submarine fiber. Another factor that contributes to the imperfect visibility is the accidental identification of coincident pairs, which reduced the visibility by $\sim 3.5\%$. The polarization mode dispersion is specified to be around 3.5% in the D/A basis. Second, the dispersion of the fiber link ($\sim 500$ ps), and other effects dominated by the timing uncertainty of the time-tagging units and their synchronization ($\sim 300$ ps), including the uncertainty of the SNSPD system in Malta ($\sim 100$ ps).

Discussion

Our results demonstrate the successful distribution of entanglement over a 96-km-long submarine optical fiber link that is part of actively used classical telecommunications infrastructure. This field demonstration marks the longest-distance distribution of entanglement in a deployed telecommunications network and demonstrates an international submarine quantum communication channel. We verified the quality of entanglement by violating the CHSH inequality at the level of 86% (2.421) and have demonstrated all of the quantum prerequisites to be able to fully implement QKD with rates of 57.5 bits per second in the asymptotic time limit. The link attenuation and QBER stayed constant for over 2.5 h without active polarization stabilization. This is in accordance with results from other groups that investigated the changes of the polarization state of buried fibers (43) and found slow drifts on the scale of hours or days. These slow drifts could be compensated for periodically by using an alignment signal as in ref. 32. The stability depends on the external conditions, since sometimes, buried or aerial fibers are found to exhibit faster polarization changes (23, 44, 45), which call for a control technique that continuously optimizes the QBER.

Based on this, we can conclusively prove that secure polarization entanglement-based quantum communication is indeed possible over comparable deployed fiber links.

While most field demonstrations of quantum cryptography in fiber were based on time-bin encoding (40, 46), our field trial was based on polarization encoding. Our results highlight the convenience of polarization-entangled qubits for future implementations of QKD networks. This is because polarization-entangled qubits are easy to measure and prepare with a high fidelity, and they can be transmitted without notable depolarization over distances of at least $\sim 100$ km as indicated by our experimental results. Nevertheless, studies mentioned above (23, 43, 44, 45) have shown that the deployed fibers have to be selected with care, as the stability of their polarization state depends on external influences. Polarization entanglement can also be used to seamlessly interface between free-space- and fiber-based communication links. Finally, one can simply make use of the many quantum repeater and quantum networking schemes that have been proposed for polarization entanglement, which can further extend the range of QKD systems and the number of clients that they can reach. As an outlook, we note that, by using commercially available detectors with improved timing resolution (47), we could more than double the distance with respect to this experiment. Our work thus opens up the

![Fig. 2.](image2.png) Coincidence count rates for one detector pair and two different detection systems. Coincident events are counted if they fall within 500 ps from the central peak position. The FWHM of $\sim 0.7$ ns is attributed to timing uncertainty of the SPADs in Sicily ($\sim 400$ ps), the dispersion of the fiber link ($\sim 500$ ps), and other effects dominated by the timing uncertainty of the time-tagging units and their synchronization ($\sim 300$ ps), including the uncertainty of the SNSPD system in Malta ($\sim 100$ ps).

![Fig. 3.](image3.png) Coincidence count rates for one detector pair and two different measurement angles in Sicily (V (red) and D (green)) as a function of the measurement angle for the analyzer in Malta, $\phi_M$, starting from H (red) or D (green). Poissonian statistics are assumed for the data as indicated by the error bars.
CHSH quantity $S_{\text{CHSH}}$ as a function of the measurement angle for the analyzer in Malta, $\phi_M$, which resembles the relative angle between the two mutually unbiased bases that were used in Malta and Sicily each. Error bars are included but fit within the data markers; the SD is $\leq 0.014$ for all of the points shown. Data outside the gray region (shown as squares) exclude local realistic theories. This function is computed using data similar to those shown in Fig. 3. The solid red curve is obtained from a fit to the coincidence rates (as in Fig. 3) and not from a fit to the data shown here, and it yields a CHSH value of $2.534 \pm 0.08$. The green horizontal line shows the CHSH value of $2.421 \pm 0.008$ obtained in a measurement run at the fixed value of $\phi_M = 157.5^\circ$ (this includes a measurement at $22.5^\circ$; i.e., the theoretically optimal angles).

possibility of using polarization entanglement for truly global-scale fiber-based quantum communication.

Materials and Methods

Entangled Photon Source. The source of polarization-entangled photons was based on spontaneous parametric down-conversion in a periodically poled lithium niobate (MgO:ppLN) crystal. To produce signal and idler pairs spanning in the telecommunications C band, type 0 quasiphase matching was used to produce, from a continuous wave pump laser with the wavelength 775.075 nm, signal and idler pairs in the telecommunication C band. The MgO:ppLN crystal was bidirectionally pumped inside a Sagnac-type setup (48) to produce the polarization-entangled Bell state. The pump power was set to 21.3 mW for the visibility measurement, 23.9 mW for the CHSH measurements, and 25.5 mW for the key rate measurement.

Due to conservation of energy during the down-conversion process, the pump energy, polarization-entangled photon pairs are found at equal spectral distance from the central frequency. We used $\sim 0.6$-nm FWHM band-pass filters to separate signal and idler photons at an equal spectral distance of the channels from the central wavelength of 1,550.15 nm. ITU WDM channel 36 ($\lambda_s = 1,548.52$ nm) was chosen for the signal photons to be sent to Sicily, while the idler photons in channel 32 ($\lambda_l = 1,551.72$ nm) were detected locally in Malta.

Locally in Malta, the visibility of the source was measured at $\sim 98\%$ in the D/A polarization basis and $97\%$ in the HV/V basis. The local heralding efficiency was $\sim 12\%$ measured on the SNSPD system; locally, 28,000 pairs were detected per milliwatt of pump power. Two SNSPDs, necessary for handling the high count rates of $1.3$ and $1.93$ million counts per second, were used in the detection system in Malta, and they were operated at efficiencies of $\sim 54$ and $59\%$, respectively, and with dark count rates of $\sim 550$ and $470$ counts per second, respectively.

Fiber Birefringence Compensation. The $(\phi)$ state was optimized locally in Malta by changing the polarization of the pump beam and characterized using the local detection module and a polarization analysis module that was inserted into the region denoted free space beam (FSB) in Fig. 1. To ensure that the quantum state can be detected at the other end of the 96-km fiber link, the polarization rotation of the quantum channel was neutralized by receiving alternately one of two mutually unbiased polarization states H and D from a laser, which was connected in the place of an APD in Sicily. The neutralization was done manually using the signal of a polarimeter placed in the region FSB and manual fiber polarization controllers.

Single-Photon Counting in Malta. The superconducting detectors used in Malta were fabricated from a newly developed 9-mm-thick NbTiN superconducting film deposited by reactive cosputtering at room temperature at the Swedish Royal Institute of Technology. The nanowires were patterned using electron beam lithography and subsequent dry etching in collaboration with Single Quantum. The fabrication process included additional fabrication steps, such as back-mirror integration and through-wafer etching for fiber alignment. We used a commercial crystal (Single Quantum Eos) operating at 2.9 K and a current driver (Single Quantum Atlas) to operate the fiber-coupled SNSPDs. The efficiency of the detectors being dependent on the photon polarization, a three-paddle fiber polarization controller was used to optimize the detection efficiency. The SNSPD system operated continuously for 2 weeks in a data center facility at an ambient temperature of about $30^\circ$C without any degradation in performance.

Single-Photon Counting in Sicily. In Sicily, two different models of free-running SPADs based on InGaAs were used due to their greater mobility compared with the cryogenic SNSPDs. However, they presented very different characteristics than the SNSPDs used in Malta in terms of efficiency and dark counts. One detector had an efficiency of $\sim 2\%$ at a dead time of $1 \mu$s and 140 dark counts per second at a count rate of $\sim 10\%$ at a dead time of $5 \mu$s with $\sim 550$ dark counts per second. The count rates including dark counts were between 590 and 890 counts per second for the detector with lower efficiency and between 2,100 and 2,300 counts per second for the detector with higher efficiency.

CHSH Measurements. To compute the $S$ value, measurements from four basis settings were combined, while coincidence counts between all four detectors were used. The CHSH inequality reads

$$-2 \leq S = E(a_1, b_1) + E(a_1, b_2) + E(a_2, b_1) - E(a_2, b_2) \leq 2,$$

while $a_i$ with $i = 1, 2$ indicates the angles in Malta with $a_1 - a_2 = 45^\circ$ and $b_1 - b_2 = 45^\circ$ in Sicily. The correlation functions $E(a_i, b_j)$ are computed from the coincidence counts $C(a_i, b_j)$ measured at the angles $a_i, b_j$ as follows:

$$E(a_i, b_j) = \frac{C(a_i, b_j) + C(a_i, b_{j+1}) - C(a_i, b_{j-1}) - C(a_i, b_j)}{C(a_i, b_j) + C(a_i, b_{j+1}) + C(a_i, b_{j-1}) + C(a_i, b_j)}$$

The symbol $\perp$ corresponds to the perpendicular angle (i.e., the second output of the polarizing beam splitter). The angle $\phi_M$ in Fig. 4 can be understood as the relative angle between the measurement bases used in Malta and Sicily and is proportional to $a_i - b_i$.

We measured the CHSH value with the analyzers set to the expected optimal settings $22.5^\circ - 157.5^\circ$ and HV/VIA (Malta–Sicily), respectively. For each measurement setting, we accumulated data for a total of 600 s. They provided enough data to break down the data series into 39 blocks per measurement setting and perform a statistical analysis of the data without relying on Poissonian count rate statistics.

Estimation of Finite Secret Key Rate. The secret key rate given in the text has been estimated based on the assumption that the setup had used a fast and random basis choice for each photon arriving at the detector. For that, two measurements of 15 s have been made, one in the D/A basis and one in the HV/V basis, to estimate the QBER for each basis. In total, this gives sifted key lengths of 3,730 bits in the HV basis and 3,857 bits in the D/A basis, which would have been measured in 60 s if the basis had switched fast and randomly. The error counts were 196 and 118 bits, respectively. The count rates observed over 15 s have been scaled to other timescales to estimate the finite-size key rate. The finite-size effect considered here is due to the fluctuations of the count rate that increase the phase error. The phase errors $\theta_0$ and $\theta_1$ have been estimated using the relations given in ref. 42, such that the probability $p_{\text{er}}$ to underestimate the phase error rate is smaller than $10^{-5}$. This allows us to calculate the key rate using an expression from ref. 41 with an error correction efficiency of 1.2 (49). After 2.9 s of measurement, the secret key rate would have been positive (41, 42), and after 60 s, the rate would be around 46 bits per second. In the asymptotic time limit, the key rate achieved is about 57.5 bits per second.

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