Experimental entanglement restoration on entanglement-breaking channels

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Quantum entanglement, a fundamental property ensuring security of key distribution and efficiency of quantum computing, is extremely sensitive to decoherence. Different procedures have been developed in order to recover entanglement after propagation over a noisy channel. However, besides a certain amount of noise, entanglement is completely lost. In this case the channel is called entanglement breaking and any multi-copy distillation methods cannot help to restore even a bit of entanglement. We report the experimental realization of a new method which restores entanglement from a single photon entanglement breaking channel. The method based on measurement of environmental light and quantum feed-forward correction can reveal entanglement even if this one completely disappeared. This protocol provides new elements to overcome decoherence effects.

The resource of quantum entanglement lies at the basis of many protocols of quantum communication and information $^1$. In order to face the problems introduced by the real world, it is primary of importance to consider the unavoidable interaction between noise and signal. The presence of noise alters or even invalidates the transmission of quantum information through communication channel, by spoiling entanglement. Nowadays many investigations have been developed in order to restore the entanglement lost, performing purification and distillation protocols $^2$. However, all these techniques can operate only on systems characterized by non-vanishing entanglement. When a channel is entanglement-breaking $^3$, that is, no entanglement is left after the interaction with noise, it is insufficient to work only at the input and output of the channel, and one has to go into the channel process and try to get more information to reveal entanglement. Thus a physical structure of the channel starts to be relevant. An interesting approach is based on an extension of quantum erasing idea $^4$, $^5$, $^6$, $^7$: a state of the system can be restored if a proper measurement is performed on the environment $^8$. This procedure, recently introduced as environmental channel correction $^9$, $^{10}$, $^{11}$, offers a theoretical possibility to deterministically restore complete entanglement. This is an interesting perspective, but the environment is normally not under complete control. Naturally, it is desirable to recover entanglement only by measuring that part of the environment which is directly and closely coupled to the signal and to relax any constraints on the environment previous to interaction and on the noise coupling. The protocol introduced here is able to restore entanglement without control on the environment previously to the interaction. Since no information is directly communicated by the entangled pair, we can reasonably relax from the deterministic correction and assume rather general probabilistic corrections, similarly as for distillation protocol.

The overall dynamic of the protocol can be divided in three different steps:

1) **Coupling with environment.** Alice (A) and Bob (B) share a polarization entangled state $|\Psi^+\rangle_{AB} = (|H\rangle_A|V\rangle_B - |V\rangle_A|H\rangle_B) / \sqrt{2}$, and the photon $B$ propagates over a noisy channel. The environment $E$ is represented by a completely unpolarized photon described by the density

![FIG. 1: Schematic representation of the entanglement restoration procedure. Generation by the EPR source of the entangled photons shared between Alice and Bob. On Bob mode is showed the interaction between the entangled photon and the environment and the measure on the environmental photon that drives the filtration process.](image-url)
matrix $\rho_E = \frac{1}{2} = |H\rangle \langle H| + |V\rangle \langle V|$ that interacts with $B$ by localizable simple linear coupling: a generic beam splitter BS with transmittivity $T$ and reflectivity $R = 1 - T$. All the results that will be presented can be directly extended for general passive coupling between the two modes. After the interaction on the beam splitter, three possible situations can be observed: both the photons go to environment or to the signal mode, or only a single photon is separately presented in signal and environment. The first case corresponds simply to attenuation, while the second case can be in principle distinguished by counting the number of photons in the signal. Thus only the last case is interesting to be analyzed. After the interaction process, the entanglement has been damaged and, below a threshold value of $T$, no entanglement can be observed in the output state.

II) Measurement of the environment. We present here a procedure which restores the entanglement by measuring the photon on the environmental mode. The photon propagating on mode $k_E$ is measured after a polarization analysis realized through a polarizing beam splitter (PBS) (Fig. 1-II). Two different scenarios will be analyzed: in the first one, the environmental photon and the signal one are distinguishable in principle but, due to technological limitations, we are not able to achieve a discrimination among them. In this situation the restoration is able to partially recover entanglement. On the other hand, when the two photons are indistinguishable, the protocol exploits quantum interference phenomena, analogously to the quantum state teleportation, and asymptotically retrieves all the initial entanglement.

III) Filtration. A key role in the protocol is represented by a filtration performed both on Alice and Bob modes. Such operation leads to a higher entanglement of the bipartite system, at the cost of a lower probability of implementation. As shown in Fig. (I-III), the filtering is achieved by two sets of glass positioned close to their Brewster’s angle, in order to attenuate one polarization ($V$) in comparison to its orthogonal ($H$). We indicate the attenuation over the mode $k_i$ for the $V$ polarization as $A_i$: $|V\rangle_i \rightarrow \sqrt{A_i}|V\rangle_i$. By tuning the incidence angle of the beam on mode $k_i$, different values of attenuations $A_i$ can be achieved. The complete protocol implies a classical feed-forward on the polarization state of the photon belonging to the mode $k_B$ depending on which detector on environmental mode ($D_E$ or $D_E'$, Fig.1-II) fires: precisely if the detector $D_E$ clicks no transformation is implemented on the quantum channel, in the other case two $\sigma_X$ are applied before and after the filtration: Fig. (I-III). This conditional operation could be realized adopting the electronic scheme experimentally demonstrated in [12, 13]. Without feedforward, the efficiency of the overall procedure is reduced by a factor 2.

The different stages of the restoration process will be described by the theoretical density matrices $\rho_{AB}$, written in the basis $\{|HH\rangle, |HV\rangle, |VH\rangle, |VV\rangle, \}$ as:

$$\rho_{AB} = \frac{1}{4P} \begin{pmatrix} \alpha & 0 & 0 & 0 \\ 0 & \beta & i\xi & 0 \\ 0 & -i\xi & \gamma & 0 \\ 0 & 0 & 0 & \delta \end{pmatrix}$$

where the parameters $\alpha, \beta, \gamma, \delta, \xi$ vary in the different protocol steps and $P$ represents a normalization parameter related to the probability of each operation. The degree of entanglement after each step is evaluated through the concurrence $C$, which assumes values $0 \leq C \leq 1$ dependently if the state is separable ($C = 0$) or entangled ($C > 0$). In particular, a maximally entangled state

![FIG. 2: Experimental setup. The main source of the experiment is a Ti:Sa mode-locked laser with wavelength (wl) $\lambda = 795nm$. A small portion of this laser, generates the single noise photon over the mode $k_E$ using an attenuator (ATT). The transformation used to map the state $|H\rangle_E$ into $\rho_E = |H\rangle_E \langle H|$ is achieved either adopting a Pockels cell driven by a sinusoidal signal, either through a stochastically rotated $\lambda/2$ waveplate [13]. The main part of the laser through a second harmonic generation (SHG) which generates a UV laser beam with wave-vector $k_p$ and power equal to 800mW. This field pump a 1.5mm thick non-linear crystal of $\beta$-barium borate (BBO) cut for type II phase-matching that generates polarization entangled pairs $|\Psi\rangle_{AB}$ with equal wavelength $\lambda = 795nm$. The spatial and temporal walk-off is compensated through a $\frac{\lambda}{4}$ waveplate and a 0.75 mm thick BBO [16]. The dashed boxes indicate the polarization analysis setup adopted by Alice and Bob. The photons are coupled to a single mode fiber and detected by single photon counting modules $D_i$. On output modes $k_E'$ and $k_E''$ the photons are spectrally filtered adopting two interference filters (IF) with bandwidth equal to 3nm, while on mode $k_s$, the IF has bandwidth 4.5nm. For indistinguishable noise photon the IF on $k_E'$ and $k_E''$ have been replaced by IF with FWHM equal to 1.5nm. The output signals of the detectors are sent to a coincidence box interfaced with a computer, which collects the different double and triple coincidence rates. The detection of triple coincidence ensures the presence of one photon per mode. \]
(a) Noise distinguishable photons

| \(\rho_{AB} \) | \(A_A \) | \(A_B \) | \(\alpha \) | \(\beta \) | \(\gamma \) | \(\delta \) | \(\xi \) | \(C \) | \(P \) |
|---|---|---|---|---|---|---|---|---|
| I | \(R^2 \) | \(R^2 + 2T^2 \) | \(R^2 + 2T^2 \) | \(R^2 \) | \(-2T^2 \) | \(0 \) | \(0 \) | \(R^2 + T^2 \) |
| II | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) |
| III | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) |

(b) Noise indistinguishable photons

| \(\sigma_{AB} \) | \(A_A \) | \(A_B \) | \(\alpha \) | \(\beta \) | \(\gamma \) | \(\delta \) | \(\xi \) | \(C \) | \(P \) |
|---|---|---|---|---|---|---|---|---|
| I | \(R^2 \) | \(1 - 4T^2 + 5T^2 \) | \(R^2 + 2T^2 - 2RT \) | \(R^2 \) | \(-2T^2 + 2RT \) | \(0 \) | \(0 \) | \(R^2 + T^2 - RT \) |
| II | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) |
| III | \(T > \{2T - 1\} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) |
| III | \(T < \{2T - 1\} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) | \(\frac{\alpha^2}{\alpha^2} \) |

Table I. Theoretical values of the elements of \(\rho_{AB} \) matrix, concurrence C, probability of success P, and intensity A of filtering on Alice and Bob mode, for the three different steps of the restoration procedure.

reaches \(C = 1 \) [14].

A schematic drawing of our experimental layout is shown in Fig.2. In order to couple the noise with the signal, the photons on modes \(k_B \) and \(k_E \) are injected in the two input arms of a beam-splitter (BS) with transmittivity \(T \). A mutual delay \(\Delta t \), micro-metrically adjustable by a two-mirror optical "trombone", can change the temporal matching between the two photons. The setting value \(\Delta t = 0 \) corresponds to the full overlapping of the photon pulses injected into BS, i.e., to the maximum photon interference.

**Distinguishable noise photons**

The experiment with distinguishable photons has been achieved by injecting a single photon \(E \) with a mutual delay with photon \(B \) of \(\Delta t >> \tau_{coh} = 300 \text{fs} \). We note that the resolution time of the detector \(\tau_{det} >> \Delta t \), hence it is not technologically possible to individuate whether the detected photon belongs to the environment or to the entangled pair.

**I** Without any access to the environmental photon, after the mixing at the beam splitter the state \(|\Psi^-\rangle_{AB} \) evolves into the density matrix \(\rho_{AB}' \) (see Table.I). As can be observed in Fig.(3-a), for \(T \leq (\sqrt{2} - 1) \) the concurrence \(C_I \) vanishes. To verify the theory we carried an experiment by adopting a beam splitter with \(T \approx 0.4 \). The experimental density matrix \(\rho_{AB}' \) is shown in Fig.(4-I) and has a high fidelity with the theoretical prediction: \(F_{I} = F(\rho_{AB}', \rho_{AB}) = (0.997 \pm 0.006) \), where \(F(\rho, \sigma) = T \rho T^{\dagger} \left[(\sqrt{\rho} \sqrt{\sigma} \sqrt{\rho})^{1/2} \right] \) represents the fidelity between two mixed states \(\rho \) and \(\sigma \). As expected, the state obtained experimentally exhibits \(C_I = 0 \), hence the communication channel is entanglement breaking.

**II** As no selection has been performed on the environment before the coupling with signal, a multimode noise interacts with the entangled photon. After the interaction, a single mode fiber has been inserted on the output mode of the BS in order to select only the output mode connected with the entanglement breaking. Let us consider the case in which the photon on mode \(k_E \) is measured in the state \(|H\rangle_E \) (Fig.1-II). The state evolves into an entangled one described by the density matrix \(\rho_{AB}' \). Theoretically, the entanglement is restored for all the values of \(T \neq 0, \frac{1}{2} \) but the elements of the matrix are fairly unbalanced. The experimental result \(\tilde{\rho}_{AB}' \) is reported in Fig.(4-II). According to theory, we expect a restoration of the entanglement with \(C_{II} = 0.32 \), and success rate \(P_{II} = 0.27 \). The experimental state \(\tilde{\rho}_{AB}'' \) is characterized by a fidelity with the theoretical one \(F_{II} = (0.96 \pm 0.06) \), which leads to \(C_{II} = (0.19 \pm 0.02) \) > 0 and \(P_{II} = (0.26 \pm 0.01) \).

**III** If \(T \) is known then the state can be further locally filter out. Two filters \(F_A \) and \(F_B \) acting on the modes \(k_A \) and \(k_B \) ensures a symmetrization of the state and a lowering of the \(|V\rangle\langle V| \) component, leading to a higher concurrence: Fig.(3-a). The intensity of filtration is quantified by a parameter \(0 < \varepsilon \leq 1 \), connected to the attenuation of \(V \) polarization. The concurrence has a limit for asymptotic filtration \(\varepsilon \rightarrow 0 \) lower than unity and maximal entanglement cannot be approached. This is a cost of reversal of entanglement for distinguishable photons. Of course, the collective protocols can be still used, since all entangled two-qubit state are distillable to a singlet one. Applying the filtration with the parameters \(A_A = 0.33 \) and \(A_B = 1 \), we obtain the final experimental state shown in Fig.(4-III). Such filtration brings to a theoretical concurrence of \(C_{III} = 0.42 \) and an overall success rate of \(P_{III} = 0.17 \). Hence we achieve a fidelity \(F_{III} = (0.89 \pm 0.06) \) and measure a concurrence equal to \(C_{III} = (0.28 \pm 0.02) > \tilde{C}_{II} \), while \(\tilde{P}_{III} \tilde{P}_{II} = (0.11 \pm 0.01) \). The experimental results shown above represent an evident prove of the restoration protocol validity, indeed an entanglement breaking channel
which is separable for $T < T^*$ into distinguishability ($T^*$ distinguishable photons where filtration applied to a mixture of indistinguishable and indistinguishable photons - without measurement (dotted line), with measurement (continuous line). (c-d) Strategy with measurement and filtration applied to a mixture of indistinguishable photons where $p$ quantifies the degree of indistinguishability ($T = 0.3$): c) concurrence, d) Probability of implementation.

**Indistinguishable noise photons**

**I** In the indistinguishable photons regime, we indicate with $\sigma_{SB}^I$ the density matrix after the mixing on the BS, which is separable for $T < 1/\sqrt{3}$ (see Table.1). The output state is found to be a Werner state, that is, a mixture of the singlet state and the fully mixed one [17].

**II** A measurement is carried out on the environmental mode. When the result $|\Psi\rangle_E$ is obtained, $\sigma_{SB}^I$ evolves into $\sigma_{SB}^{II}$. The Werner state is conditionally transformed into a maximally entangled state (MEMS) [14].

**III** Due to the strong unbalance of $\sigma_{SB}^{II}$ a filter is introduced either on Alice or Bob mode, depending on the value of $T$: Fig.(2). In the limit of asymptotic filtration ($\varepsilon \rightarrow 0$), the concurrence reaches unity except for $T = 1/2$ (Fig. 3-b). Since maximally entangled state can be corrected to a channel preserving relatively large amount of the entanglement.

**General Case**

Let us now face up to a model which contemplates a situation close to the experimental one. We consider the density matrix $\tau_{AB}$ of the state shared between Alice and Bob after the coupling with the environment, as a mixture arising from coupling with a partially distinguishable noise photon. The degree of indistinguishability is parametrized by the probability $p$ that the fully depolarized environmental photon is completely indistinguishable from signal: Fig.(3-c-d).

**FIG. 3:** (a-b) Concurrence for different scenarios a) Distinguishable photons - without measurement (dotted line), with measurement (dashed -dotted line), with measurement and filtration $\varepsilon = 0.15$ (dashed line), with measurement and filtration $\varepsilon \rightarrow 0$ (continuous line). b) Indistinguishable photons - without measurement (dotted line), with measurement (dashed -dotted line), with measurement and filtration $\varepsilon = 0.25$ (dashed line), with measurement and filtration $\varepsilon = 0.05$ (continuous line). (c-d) Strategy with measurement and filtration applied to a mixture of indistinguishable and distinguishable photons where $p$ quantifies the degree of indistinguishability ($T = 0.3$): c) concurrence, d) Probability of implementation.

**FIG. 4:** Experimental density matrix for distinguishable photons: a) $\widetilde{\rho}^{iin}_{AB}$, b) $\bar{\rho}^I_{AB}$, c) $\bar{\rho}^{III}_{AB}$. The fidelity with the entangled state $|\Psi^+\rangle_{AB}$ is $F(\rho^I_{AB}, |\Psi^+\rangle_{AB}) = \langle \Psi^+ |_{AB} \bar{\rho}^{I}_{AB} \bar{\rho}^{I}_{AB} |\Psi^+\rangle_{AB} = (0.915 \pm 0.002)$ while the concurrence [14] reads $C = (0.869 \pm 0.005)$. The uncertainties on the different observables have been calculated through numerical simulations of counting fluctuations due to the poissonian distributions. We reconstruct the two qubit density matrix $\rho_{AB}$ through the quantum state tomography procedure [18]. An overcomplete set of observables is measured by adopting different polarization settings of the $\hat{H}_\| \omega$ and $\hat{H}_\perp \omega$ positions. For each tomographic setting the measurement lasts from 5 s (a) to 30 minutes (c), the last case corresponding to about 500 triple coincidence. Contributions due to triple accidental coincidences have been subtracted from experimental data.
Comparing both the discussed indistinguishable and distinguishable photons, it is evident that it can be advantageous to induce indistinguishability. For example, if they are distinguishable in time, then spectral filtering can help us to make them more indistinguishable and consequently, the entanglement can be enhanced more by local filtering. In order to ensure a high indistinguishability between the photon of modes \( k_B \) and \( k_E \), we adopt narrow band interference filters (Fig.2). We have estimated the degree of distinguishability between the photon belonging to mode \( k_B \) and the one associated to \( k_E \) as \( p = (0.85 \pm 0.05) \) by realizing an Hong-Ou-Mandel interferometer adopting a beamsplitter with \( T = 0.5 \). We attribute the mismatch of \( p \) with the unit value to a different spectral profile between the coherent beam and the fluorescence. To carry out the experiment we adopt a beamsplitter with \( T = 0.3 \) and the optical delay has been set in the position \( \Delta t = 0 \). I) The input singlet state evolves into a noisy one represented by \( \tilde{\rho}_{AB} \) characterized by a fidelity with theory \( F(\tilde{\rho}_{AB}, \rho_{AB}) = (0.86 \pm 0.02) \) and vanishing concurrence \( (C = 0) \). II) After measuring the photon on mode \( k_B \), the density matrix \( \tilde{\rho}_{AB} \) evolves into \( \tilde{\rho}_{AB}^{II} \). The entanglement is restored with a concurrence equal to \( \tilde{C}_{II} = (0.15 \pm 0.03) > 0 \) to be compared with \( C_{II} = 0.22 \); in this case the probability of success reads \( P_{II} = (0.22 \pm 0.01) \), theoretically \( P_{II} = 0.2 \). The fidelity with the theoretical state is \( F(\tilde{\rho}_{AB}^{II}, \rho_{AB}^{II}) = (0.96 \pm 0.01) \). III) Applying the filtration with the parameters \( A_B = 0.12 \), and \( A_B = 0.30 \) we obtain the state shown in Fig. (5-III). Hence we measure a higher concurrence \( \tilde{C}_{III} = (0.50 \pm 0.10) > \tilde{C}_{II} \) while the expected theoretical value is \( C_{III} = 0.47 \). The filtered state has

\[
F(\tilde{\rho}_{AB}^{II}, \tilde{\rho}_{AB}) = (0.92 \pm 0.04),
\]

and is postselected with an overall success rate equal to \( P_{III} = (0.20 \pm 0.002) \), where theoretically \( P_{III} = 0.016 \). This is a clear experimental demonstration of how an induced indistinguishability enhances the restored concurrence after an entanglement breaking channel.

In summary, we have reported the experimental demonstration of a new protocol able to restore entanglement on entanglement breaking channel by measuring the information leaking out into the environment. The restoration entanglement procedure can contribute to develop a new class of measurement-induced operations, based on cross application of single-photon detection and feed-forward. Even for the channel preserving entanglement, it can be particularly advantageous to detect environmental state outgoing from the coupling, because the entanglement can be increased simply by local filtering on single copy instead of more demanding collective distillation protocol. The present scheme can be generalized to restore entanglement after consecutive interactions with different sources of noise by properly measuring the outgoing environment. Moreover, a direct application can be envisaged in quantum computation with matter devices, where decoherence can be attributed to coupling of signal qubits with other degrees of freedom of the information carrier. In this framework, a measurement on this available environment can be adopted to retrieve entanglement. On the fundamental side the present experiment provide new elements to overcome decoherence effects, a subject of renewed interest in the last year [22, 23].

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[1] Horodecki, R., Horodecki, P., Horodecki, M., Horodecki, K., Quantum Entanglement, [quant-ph 0702225]
[2] Pan, J. W., Gasparoni, S., Ursin, R., Weihs, G., and Zeilinger, A., Experimental entanglement purification of arbitrary unknown states. Nature 423, 417 (2003).
[3] Horodecki, M., Shor, P.W., Ruskai, M.B., General Entanglement Breaking Channels. Rev. Math. Phys 15, 629 (2003).
[4] Scully, M. O., Englert, B. G., and Walther, H., Quantum optical tests of complementarity. Nature (London) 351, 111 (1991).
[5] Englert, B. G., Scully, M. O., and Walther, H., Complementarity and uncertainty. Nature (London) 376, 367 (1995).
[6] Zajonc, A. G., et al., Quantum eraser. Nature (London) 353, 507 (1991).
[7] Kwiat, P. G., Steinberg, A. M., and Chino, R. Y., Observation of a quantum eraser: A revival of coherence in a two-photon interference experiment. Phys. Rev. A 45,
[8] Gregoratti, M., and Werner, R.F., Quantum Lost and Found. J. Mod. Opt. 50, 915 (2003).

[9] Buscemi, F., Chiribella, G., and D’Ariano, G. M., Inverting quantum decoherence by Classical Feedback from the Environment, Phys. Rev. Lett. 95, 090501 (2005).

[10] Hayden, P., and King, C., Correcting quantum channels by measuring the environment. Quantum Inform. Comput. 5, 156 (2005).

[11] Smolin, J.A., Verstraete, F., and Winter, A., Entanglement of Assistance and Multipartite State Distillation. Phys. Rev. A 72, 052317 (2005).

[12] Giacomini, S., Sciarrino, F., Lombardi, E., and De Martini, F., Active teleportation of a quantum bit. Phys. Rev. A 66, 030302(R) (2002).

[13] Sciarrino, F., Ricci, M., De Martini, F., Filip, R., and Mista, L., Realization of a Minimal Disturbance Quantum Measurement. Phys. Rev. Lett. 96, 020408 (2006).

[14] Wootters, W., Entanglement of Formation of an Arbitrary State of Two Qubits. Phys. Rev. Lett. 80, 2245 (1998).

[15] Sciarrino, F., Sias, C., Ricci, M., and De Martini, F., Realization of universal optimal quantum machines by projective operators and stochastic maps. Phys. Rev. A 70, 052305 (2004).

[16] Kwiat, P. G., Mattle, K., Weinfurter, H., and Zeilinger, A., New High-Intensity Source of Polarization-Entangled Photon Pairs. Phys. Rev. Lett. 75, 4337 (1995).

[17] Werner, R. F., Quantum states with Einstein-Podolsky-Rosen correlations admitting a hidden-variable model. Phys. Rev. A 40, 4277 (1989).

[18] James, D. F. V., Kwiat, P. G., Munro, W. J., and White, A. G., Measurement of qubits. Phys. Rev. A 64, 052312 (2001).

[19] Verstraete, F., Audenaert, K., De Bie, T., and De Moor, B., Maximally Entangled Mixed States of Two Qubits. Phys. Rev A 64, 012316 (2001).

[20] Verstraete, F., Dehaene, J., and DeMoor, B., Local filtering operations on two qubits. Phys. Rev A 64, 010101 (2001).

[21] Hong, C. K. Z., Ou, Y., and Mandel, L., Measurement of subpicosecond time intervals between two photons by interference. Phys. Rev. Lett. 59, 2044 (1987).

[22] Almeida, M. P., et al., Environment-Induced Sudden Death of Entanglement. Science 316, 579 (2007)

[23] Konrad, T., et al., Evolution equation for quantum entanglement. Nature 4, 99 (2008)