Experimental violation of local causality in a quantum network

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Bell's theorem plays a crucial role in quantum information processing and thus several experimental investigations of Bell inequalities violations have been carried out over the years. Despite their fundamental relevance, however, previous experiments did not consider an ingredient of relevance for quantum networks: the fact that correlations between distant parties are mediated by several, typically independent sources. Here, using a photonic setup, we investigate a quantum network consisting of three spatially separated nodes whose correlations are mediated by two distinct sources. This scenario allows for the emergence of the so-called non-bilocal correlations, incompatible with any local model involving two independent hidden variables. We experimentally witness the emergence of this kind of quantum correlations by violating a Bell-like inequality under the fair-sampling assumption. Our results provide a proof-of-principle experiment of generalizations of Bell's theorem for networks, which could represent a potential resource for quantum communication protocols.

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As demonstrated by the celebrated Bell’s theorem\(^1\), correlations arising from experiments with distant quantum mechanical systems are at odds with one of our most intuitive scientific notions, that of local realism. The assumption of realism formalizes the idea that physical quantities have well-defined values independently of whether they are measured or not. In turn, local causality posits that correlations between distant particles can only originate from causal influences in their common past. These two rather natural assumptions together imply strict constraints on the empirical correlations that are compatible with them. These are the famous Bell inequalities, which have been recently violated in a series of loophole-free experiments\(^2\)–\(^4\) and thus conclusively established the phenomenon known as Bell non-locality. Apart from their profound implications in our understanding of nature, such experiments provide a proof-of-principle for practical applications of non-local correlations, most notably in the context of quantum networks\(^5\)–\(^7\).

In a quantum network, short-distance nodes are connected by sources of entangled systems which can, via an entanglement swapping protocol\(^8\)–\(^9\), establish entanglement across long distances as well. Importantly, such long-distance entanglement can in principle also be used to violate a Bell inequality and thus establish a secure communication channel\(^10\)–\(^12\). Clearly, for these and many other potential applications\(^13\)–\(^16\), the certification of non-local correlations across the network will be crucial. The problem, however, resides on the fact that experimental imperfections accumulate very rapidly as the size of the network and the number of sources of states increase, making the detection of Bell non-locality very difficult or even impossible by usual means\(^17\),\(^18\). One of the difficulties stems from the derivation of Bell inequalities themselves, where it is implicitly assumed that all the correlations originate at a single common source (see Fig. 1b), the so-called local hidden variable (LHV) model. Notwithstanding, in a network a precise description must source (see Fig. 1b), the so-called local hidden variable (LHV) model of the form

\[
p(a, b, c|x, y, z) = \sum_{\lambda} p(\lambda)p(a|x, \lambda)p(b|y, \lambda)p(c|z, \lambda).
\]

The hidden variable \(\lambda\) subsumes all the relevant information in the physical process and thus includes the full description of the source producing the particles as well as any other relevant information for the measurement outcomes.

In the description of the LHV model (equation (1)), no mention is made about how the physical systems have been produced at the source. For the network we consider here (see Fig. 1c), the two sources produce states independently, thus the set of classically allowed correlations

\[
p(a, b, c|x, y, z) = \sum_{\lambda_1, \lambda_2} p(\lambda_1)p(\lambda_2)p(a|x, \lambda_1)p(b|y, \lambda_1, \lambda_2)p(c|z, \lambda_2),
\]
is now mediated via two independent hidden variables \( \lambda_1 \) and \( \lambda_2 \) (ref. 19), thus defining a bilocal hidden variable model.

In our scheme, Bob always performs the same measurement (no measurement choice) obtaining four possible outcomes that can be parameterized by two bits \( b_0 \) and \( b_1 \). Alice and Charlie can choose each time one of two possible dichotomic measurements. Thus, in this case the observable distribution containing the full information of the experiment is given by \( p(a, b_0, b_1, c(x, z)) \). This allows us to violate the bilocal causality inequality proposed in ref. 19 and further developed in refs 20,22–25:

\[
B = \sqrt{|I| + \sqrt{|J|}} \leq 1
\]

(3)

The terms \( I \) and \( J \) are sums of expectation values, given by

\[
I = \frac{1}{4} \sum_{x, z} \langle A_x B_y C_z \rangle \quad \text{and} \quad J = \frac{1}{4} \sum_{x, z} (-1)^{x+z} \langle A_x B_y C_z \rangle,
\]

where \( \langle A_x B_y C_z \rangle = \sum_{a, b_0, b_1, c(x, z)} (-1)^{x+z} p(a, b_0, b_1, c(x, z)) \) and \( x, z, a, b_0, b_1, c = 0, 1 \). Inequality (equation (3)) is valid for any classical model of the form (equation (2)) and its violation demonstrates the non-local character of the correlations we produce among the network.

**Violation of the bilocal causality inequality.** We generate entangled photon pairs via type-II spontaneous parametric down-conversion process occurring in two separated nonlinear crystals (Einstein-Podolsky-Rosen (EPR) 1 and EPR 2) injected by a pulsed pump laser (see Fig. 2). When a pair of photons is generated in each of the crystals, one photon from source EPR 1 (EPR 2) is sent to Alice’s (Charlie’s) measurement station, where polarization analysis in a basis that can be rotated of an arbitrary angle \( \theta^A \) (\( \theta^C \)) is performed (see Supplementary Note 1). The other two photons (2 and 3) are sent to Bob’s station, which consists of an in-fibre 50/50 beam splitter (BS) followed by two polarizing BSs for the polarization analysis of each of the outputs. In the ideal case (which relies on perfect photons’ indistinguishability), an incoming \( |\Psi^-\rangle \) (singlet) state will feature antibunching, giving rise to coincidence counts at different outputs of the BS. All the other cases (triplet states) will experience bosonic bunching, ending up in the same BS output (see Supplementary Note 1). A twofold coincidence corresponding to different polarizations in a single BS output branch corresponds to \( |\Psi^+\rangle \) detection. A half-wave plate placed before one of the arms of the BS allows, by setting \( \theta^B = 45^\circ \), to change the incoming state from \( |\Phi^+\rangle \) to \( |\Psi^-\rangle \) and from \( |\Phi^-\rangle \) to \( |\Psi^+\rangle \). In this way, depending on the setting \( \theta^B \), we are able to detect either \( |\Psi^+\rangle \) and \( |\Psi^-\rangle \) or \( |\Phi^+\rangle \) and \( |\Phi^-\rangle \) states. This detection can be interpreted as a probabilistic Bell-state measurement, where, for each pair of incoming photons, only two out of four outcomes can be unambiguously identified.

In the ideal case, Bob should be able to distinguish between all of the four Bell states, but this cannot be done by means of linear optics26. By this approach, however, we are able to measure all the combinations \( \langle A_0, C_0 \rangle , \langle A_0, C_1 \rangle , \langle A_1, C_0 \rangle , \langle A_1, C_1 \rangle \) of the observables \( A_0 = C_0 = (\sigma_x + \sigma_y)/\sqrt{2} \) and \( A_1 = C_1 = (\sigma_x - \sigma_y)/\sqrt{2} \) of Alice and Charlie, for the two possible \( \theta^B \) configurations. The fair-sampling assumption allows us to reconstruct from these data the probability \( p(a, b_0, b_1, c(x, z)) \) and then to compute the quantities \( I \) and \( J \), which appear in equation (3).

The maximum value reached in our experimental setup was \( B = 1.268 \pm 0.014 \), corresponding to a violation of inequality (equation (3)) of almost 20 sigmas. This value is fully compatible with a theoretical model that considers both colored and white noise in the state generated by the spontaneous parametric down-conversion process sources and takes into account the partial distinguishability of the generated photons (see Supplementary Note 2).

Next, we address the robustness of the bilocal causality inequality violation with respect to experimental noise. To this aim, we tuned the noise in the Bell-state measurement by modifying the temporal overlap between photons 2 and 3. This can be achieved by using a delay line before one of the two inputs of the BS, thus controlling the temporal delay between these photons (see Fig. 2). We can therefore define a noise parameter \( \rho \), which is equal to 1 in the ideal case of a perfect Bell-state measurement and is equal to 0 when the probability of having a
Both $I$ (equation (3)), whereas error bars indicates 1 s.d. of uncertainty, due to Poissonian statistics. Preparing and varying the other noise parameter optimized (orange squares) measurements settings. Theoretical predictions are shown by blue- and orange-shaded regions compatible with our state preparation and varying the other noise parameter. The regions are obtained considering the propagation of the uncertainty in the experimental estimation of noises and are bounded by 1 s.d. upper (dashed) and lower (line) curves. The dotted horizontal line indicates the bound of the inequality (equation (3)), whereas error bars indicates 1 s.d. of uncertainty, due to Poissonian statistics. (b) Measured values in the I–J plane. Error bars show 1 s.d. for both I and J values. The dashed line bounds the bilocal region as prescribed by inequality (equation (3)). Green lines define the local set and the white area represents correlations, which are compatible with local models but incompatible with bilocal causality assumption. The grey area shows the set of correlations, which are incompatible with both local and bilocal models.

Successful measurement is 1/2. This parameter can be tuned from $\rho_{\text{max}}$ to zero by changing the delay from zero to a value larger than the coherence time of the photons.

The measured values of $B$ versus $p$ are shown in Fig. 3a. As expected, the violation decreases with increasing noise. This plot shows two sets of different data points: considering a fixed measurement basis (optimal in the absence of the additional noise) and optimizing the measurement basis at Alice and Charlie’s stations as a function of $p$, that is, changing the measurement basis in order to counteract noise effects (see Supplementary Note 2). In both cases, our setup can tolerate a substantial amount of noise before inequality (equation (3)) is not violated anymore, but it is clear how the optimization increases both the degree and region of bilocal causality violation.

Another relevant way to visualize the non-bilocal correlations generated in our experiment and its relation to usual local models is displayed in Fig. 3b. A bilocal model (defined by equation (2)) must respect the inequality $\sqrt{|I|} + \sqrt{|J|} \leq 1$, while a standard LHV model (defined by equation (1)) in turn fulfills $|I| + |J| \leq 1$. As shown in Fig. 3b, the measured values of $I$ and $J$ are clearly incompatible with bilocal causality (apart from the cases with the highest amount of noise) and behave in good agreement with the theoretical model. Moreover, it clearly shows how optimizing the measurement settings improves the robustness of violation against noise.

Characterizing non-bilocal correlations against LHV models.

The data in Fig. 3b show that the observed values for $I$ and $J$ do not violate the corresponding LHV inequality. However, this only represents a necessary condition. To definitively check whether we are really facing a new type of local causality violation beyond the standard LHV model (equation (1)), we also checked that all Bell inequalities defining our scenario are not violated in the experiment. In general, given an observed probability distribution, it is a simple linear program to check if it is compatible with LHV model (see, for example, ref. 27 for further details). Equivalently, noticing that a LHV model defines a polytope of correlations compatible with it, one can derive all the Bell inequalities constraining $p(a, b_0, b_1, c|x, z)$ compatible with LHV models. Apart from trivial ones, there are 61 of these inequalities and we have checked for all the collected data with different noise parameter $p$ whether they are violated. The results are shown in Fig. 4a. It can be seen that none of the points (even those that do violate the bilocal causality inequality (equation (3))), as shown in Fig. 3 show any significant evidence (taking into account the size of the error bars) for the violation of any of the all LHV constraints.

Finally, we addressed the question whether, in an entanglement swapping scenario, bilocal causality violation could represent a stronger test rather than the usual CHSH violation, in order to certify non-local correlations in presence of experimental noise. We therefore performed a tomography of the quantum state shared between Alice and Charlie upon conditioning on Bob’s outcome (that is, entanglement swapped state) followed by an experimental test of bilocal causality (see Supplementary Note 4). This allows us to compare our experimental bilocal causality violation with the maximum possible CHSH of the swapped state in different regimes of noise. Figure 4b clearly shows the existence of quantum states, which violate bilocal causality (even without any settings’ optimization) but cannot violate the CHSH inequality, thus turning unfeasible any protocol based on its violation.

Discussion

Our results provide an experimental proof-of-principle for network generalizations of Bell’s theorem. However, similarly to any Bell test, our violation of the bilocal causality inequality is subjected to loopholes, in particular the locality and detection efficiency loopholes, as the parties are not space-like separated and we make use of the fair-sampling assumption. Given the nature of our experiment, a new loophole—similar to the measurement independence loophole in Bell’s theorem—is also introduced if the sources of states cannot be guaranteed to be truly independent. Regarding usual Bell tests, it was not until recently that such loopholes were finally overcome. Thus, from the practical perspective it would be highly desirable to design future experiments achieving that also for more complex networks.
From a fundamental perspective, recent results\textsuperscript{31,27,33–40} at the interface between quantum theory and causality have shown that Bell’s theorem represents a very particular case of much richer and broader range of phenomena that emerge in complex networks and that hopefully will lead to a deeper understanding of the apparent tension between quantum mechanics and our notions of causal relations. Furthermore, given the close connections between causal inference and machine learning\textsuperscript{41}, it is pressing to consider what advantages the recent progresses in quantum machine learning\textsuperscript{42,43} can provide in such a causal context.

From a more applied perspective, such generalizations offer an almost unexplored territory and it is still unclear how to use this new form of non-local correlations in information processing. As we showed here, we can still violate a bilocal causality inequality even if the data admits a LHV model where the independence of the sources is not taken into account. That is, quantum states generating classical correlations in conventional scenarios can become powerful resources in a network, thus hopefully enlarging our current capabilities to process information in a non-classical way. For instance, a natural next step is to experimentally realize even larger quantum networks as the one shown in Fig. 1d. For sufficiently long networks, the final quantum state swapped between the end nodes may be separable and thus irrelevant as a quantum resource. Still, the correlations in the entire network might be highly non-local\textsuperscript{25}, allowing us to probe a whole new regime in quantum information processing. Finally, we notice that during the review process of this work, an independent experimental investigation of the bilocal causality violation has appeared\textsuperscript{44}.

\textbf{Methods}

\textbf{Experimental details.} Photon pairs were generated in two equal parametric down conversion sources, each one composed by a nonlinear crystal beta barium borate (BBO) injected by a pulsed pump field with $\lambda = 392.5$ nm. The data shown in Figs 3 and 4a and the purple point in Fig. 4b were collected by using 1.5 mm-thick BBO crystals, whereas for the red and blue points in Fig. 4b we used 2 mm-thick crystals to increase the generation rate. After spectral filtering and walkoff compensation, photons are sent to the three measurement stations. The observable $A_3$, that is, $(\sigma_x + \sigma_y)/\sqrt{2}$, corresponds to a half-wave plate rotated by $\theta_1 = 11.25^\circ$, whereas $A_y$, that is, $(\sigma_x - \sigma_y)/\sqrt{2}$, corresponds to $\theta_2 = 78.75^\circ$. Analogously, $C_b$ and $C_c$ can be measured at Charlie’s station using the same angles $\theta_2 = \theta_3$ and $\theta_1 = \theta_4$. From dark blue ($p = 1$, that is, absence of noise), to light blue ($p = 0$, that is, maximum noise). Theoretical predictions are shown in the background, the red to yellow colour transition representing the dependence from $p$. Squares (circles) represent those points, which violate (do not violate) the bilocal causality inequality (equation (3)). (b) Comparison between experimental bilocal causality parameter and maximized CHSH parameter (multiplied by a factor 1/2 so that the local bound of the CHSH inequality is set to 1) in different regimes of noise. Bilocal causality test is performed with fixed non-optimized measurement settings, whereas CHSH maximum parameter is computed applying the Horodecki criterion (ref. 30) to a partial quantum state tomography (red points) or a complete quantum-state tomography (blue points) of the quantum state shared between A and C after the entanglement swapping protocol (that is, conditioned on singlet state outcome in station B). The purple point was evaluated directly testing both bilocal causality and CHSH in a particular regime of low noise. Circles (squares) represent entangled (separable) quantum states, where the degree of entanglement was computed via the partial transpose\textsuperscript{46}. The lower-left region is compatible with both models, the upper-left region denotes incompatibility with bilocal causality, the upper-right region denotes violation of both the bilocal causality and CHSH inequalities, whereas the lower-right region is characterized by only CHSH violation. Error bars indicates 1 s.d. of uncertainty, due to Poissonian statistics.
Data availability. The data that support the findings of this study are available from the corresponding author upon request.

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Acknowledgements
We thank S. Lloyd and C. Branciard for very useful discussions. This work was supported by the ERC-Starter Grant 3D-QUEST (3D-Quantum Integrated Optical Simulation; grant agreement number 307783); http://www.3dquest.eu. G.C. thanks Becas Chile and Conicyt for a doctoral fellowship. R.C. acknowledges financial support from the Excellence Initiative of the German Federal and State Governments (Grants ZUK 43 and 81), the FQXi Fund, the US Army Research Office under contracts W911NF-14-1-0098 and W911NF-14-1-0133 (Quantum Characterization, Verification, and Validation), the DFG (GEO 4334 and SPP 1798) and the brazilian ministries MEC and MCTI.

Author contributions
G.C., L.S., F.A., M.B. and F.S. performed the experiment. F.A., G.C., L.S., M.B., R.C. and F.S. developed the theoretical tools. All the authors discussed the results and contributed to the writing of the manuscript.

Additional information
Supplementary Information accompanies this paper at http://www.nature.com/naturecommunications

Competing interests: The authors declare no competing financial interests. One of the authors, M.B., is an editor on the staff of Nature Communications, but was not in any way involved in the journal review process.

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How to cite this article: Carvacho, G. et al. Experimental violation of local causality in a quantum network. *Nat. Commun.* 8, 14775 doi: 10.1038/ncomms14775 (2017).

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