Direct Counterfactual Communication with Single Photons

Yuan Cao,1,2 Yu-Huai Li,1,2 Zhu Cao,3 Juan Yin,1,2 Yu-Ao Chen,1,2 Xiongfeng Ma,3 Cheng-Zhi Peng,1,2 and Jian-Wei Pan1,2

1Shanghai Branch, National Laboratory for Physical Sciences at Microscale and Department of Modern Physics, University of Science and Technology of China, Shanghai, China
2Synergetic Innovation Center of Quantum Information and Quantum Physics, University of Science and Technology of China, Hefei, Anhui, China.
3Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, China.

(Dated: March 21, 2014)

Intuition in our everyday life gives rise to a belief that information exchanged between remote parties has to be carried by physical particles. Surprisingly, by recent theoretical studies, quantum mechanics allows counterfactual communication even without actual transmission of physical particles. The mystery of counterfactual communication stems from a (non-intuitive) fundamental concept in quantum mechanics — wave-particle duality. All particles can be fully described by wave functions. To determine whether a light appears in a channel, one is referring to the amplitude of its wave function; whereas in counterfactual communication, the information is carried by the phase part of the wave function. Using a single photon source, we experimentally demonstrate counterfactual communication and successfully transfer a monochrome bitmap from one location to another by employing a nested version of the quantum Zeno effect. Besides of its fundamental interest, our experimental scheme is applicable to other quantum technologies, such as imaging and state preparation.

The counterfactual phenomena was first presented as interaction-free measurements using a Mach-Zehnder interferometer, where the achievable efficiency is limited by 50%. Later, the efficiency is improved to 100% with the help of the quantum Zeno effect, in which a physical state experiences a series of weak measurements. When the measurements are weak enough, the state is “freezed” to its initial state with a high probability. The scheme was later applied to quantum interrogation, quantum computation, and quantum cryptography. Unfortunately, none of these schemes can be used for direct counterfactual communication, since particles would appear in the channel when information is transmitted. This challenge is solved by the recent breakthrough on direct counterfactual quantum communication by Salih, Li, Al-Amri, and Zubairy (SLAZ). The heart of the SLAZ scheme is the nested version of the quantum Zeno effect by utilizing a tandem interferometer nest. Such scheme requires an infinite number of tandem interferometers, which is impractical. Furthermore, the total visibility degrades exponentially with the number of interferometers. Here, we simplify the SLAZ scheme while preserving its counterfactual property with a nested polarization Michelson interferometer using a single photon source.

The schematic diagram of the simplified SLAZ scheme is shown in Fig. A. Alice sends a single photon in the nested interferometer and detects it with three single-photon detectors, D0, D1 and Df. If detector D0 or D1 clicks, Alice concludes logic 0 or 1, respectively. Otherwise if detector Df clicks, Alice obtains an inconclusive result, which will be discarded in the data postprocessing. Denote the numbers of beam splitters (BS) in the outer and inner cycles as M and N, respectively. The reflectivity of each outer BS is \( \cos^2(\pi/2M) \) and that of each inner BS is \( \cos^2(\pi/2N) \).

In the case of logic 0, Bob puts the mirrors in the corresponding positions so that the transmission channel is clear, as shown in Fig. B. In the limit of infinite M and perfect interference, the single photon will go to D0 with probability one. A finite M may cause erroneous event,
where $D_1$ clicks for logic 0. And a finite $M$ allows a photon to pass through the channel with a non-zero probability, in which case, due to the interference of Route 2 and Route 3, the photon can be only detected by $D_f$. In the case where information successfully transferred from Bob to Alice, no photon will pass through the transmission. That is, the counterfactual property is preserved in the case of logic 0 for finite $M$ and $N$ when single photons are used.

In the case of logic 1, Bob removes the mirrors and then the inner interferometer cycle is broken, as shown in Fig. 1. Then the transmission channel is broken and hence any detection on Alice’s side is not caused by photons transmitted through channel. That is, the counterfactual property is preserved for the case of logic 1 in practical case. If $N$ goes to infinite and the interferometer is perfect, the probability of the single photon goes to $D_1$ tends to 100%. An imperfect interferometer may cause erroneous event, where $D_0$ clicks for logic 1.

In summary, no photons pass through the transmission channel (Route 3) when Alice is able to learn the logic state (pass or block) of Bob’s setting. Considering that errors of logic 0 is only relating to the number of logic state (pass or block) of Bob’s setting. Considering channel (Route 3) when Alice is able to learn the three times, which can be realized as follows. Step 1, a photon needs to pass the nested Michelson interferometer is perfect, the probability of the single photon goes to infinite and the interferometer for exactly three times ($D_0$) when single photons are split into two spatial modes by a polarizing beam splitter (PBS) to realize the function of a biased BS. According the SLAZ scheme[1], we align the optical axis of two quarter-wave plates, $Q_1$ and $Q_2$, to $\pi/16$ as for $M = 4$, and that of a half-wave plate $H_1$ to $\pi/8$ as for $N = 2$, as shown Fig. 2.

On Bob’s side, a liquid crystal phase modulator (LCPM) and a PBS are used to realize the active choice between the two states, Pass (logic 0) and Block (logic 1). If Bob chooses logic 1, in order to block the transmission channel, the LCPM applies a $\pi$-phase delay on the arrived photon, converting the polarization from horizontal (H) to vertical (V). Then the photon will be reflected by $P_1$ and discarded, so that the transmission channel is broken. Otherwise, the LCPM does not affect the arrived photon. On Alice’s side, she records bit 0 on the coincident detection of $D_0$ and $D_1$, and bit 1 on the coincident detection of $D_1$ and $D_t$.

The nested interferometer requires stability in the sub-wavelength order to maintain a high visibility for counterfactual communication. To suppress mechanical vibration and temperature drift, we employ a technique of active phase locking in the experiment. An additional phase-locking laser with the same wavelength as the single photon source is coupled into the inner and outer interferometer. Mirrors $M_1$ and $M_B$ are placed on two piezoelectronics translation stage that can precisely adjust the interferometers according to the feedback signal. A
viscosity comparison of interferometers with and without the active phase-locking technique is shown in Fig. 2B. With the technique, the visibility can maintain 98% for hours.

In our experiment, we demonstrate direct counterfactual communication by transmitting a 100 x 100 pixel monochrome bitmap (Chinese knot), as shown in Fig. 3. Bit by bit, Bob controls his LCPM according to 10 Kbits bitmap information. After Alice obtained a successful detection event, either $D_0$ and $D_t$ click or $D_1$ and $D_t$ click, she sends Bob a feedback and then Bob continues on the next bit until the 10 Kbits information is all transmitted.

In ideal case of the SLAZ scheme when $M = 4$ and $N = 2$, the probability for Alice to rightfully identify Bob’s logic 0 is 85.4% and logic 1 is 100%. In our experiment, due to imperfect interference of the interferometer, these two numbers are reduced to 83.4% and 91.2% for logic 0 and 1, respectively. As shown in Fig. 4, the Chinese knot bitmap is successfully transmitted from Bob to Alice with high visibility.

In our current realization of counterfactual communication, the information transmitted is classical. When Bob’s logical state is “quantum” so that it can be in the superposition of pass (logic 0) and block (logic 1), an interesting question to ask is that whether counterfactual communication can also transmit quantum information. Such quantum communication scheme can also be viewed as a quantum remote state preparation scheme.

The mysterious phenomenon of counterfactual communication can also be understood from the imaging point of view. Traditionally, a typical photography tool, such as camera, records the light intensity that contains the object information. In 1940s, a new technique — holography — is developed to record not only the intensity but also the phase of the light [11], which enables 3-D imaging. Now, one can ask a question: can the phase of the light itself be used for imaging? The answer is yes from our experiment demonstration. Therefore, our counterfactual communication setup can be viewed as a phase imaging tool, where the intensity information is irrelevant. Such technique might be useful in some practical situations, such as imaging ancient arts where lights are not allowed to shine on.

We acknowledge insightful discussions with T.-Y. Chen, H.-L. Yin, Q. Zhang, Z. Zhang, and B. Zhao. This work has been supported by the National Basic Research Program of China Grants No. 2011CB921300, No. 2013CB336800, No. 2011CBA00300 and No. 2011CBA00301, the National Natural Science Foundation of China Grants No. 61073174, No. 61033001, and No. 61061130540, and the Chinese Academy of Sciences.
FIG. 3. Experiment direct counterfactual communication, transmitting a Chinese knot image. (A) The original and transferred images are compared. The black pixel is defined as logic 0, while the white one is defined as logic 1. (B) The probabilities of successfully transmitting logic 0 and logic 1. The experiment results are compared with theoretical limits.

* These authors contributed equally to this work

[1] H. Salih, Z.-H. Li, M. Al-Amri, and M. S. Zubairy, Phys. Rev. Lett. 110, 170502 (2013)
[2] R. Dicke, Am. J. Phys. 49, 925 (1981).
[3] A. Elitzur and L. Vaidman, Foundations of Physics 23, 987 (1993)
[4] P. Kwiat, H. Weinfurter, T. Herzog, A. Zeilinger, and M. A. Kasevich, Phys. Rev. Lett. 74, 4763 (1995)
[5] B. Misra and E. C. G. Sudarshan, Journal of Mathematical Physics 18, 756 (1977).
[6] A. Peres, American Journal of Physics 48, 931 (1980).
[7] G. S. Agarwal and S. P. Tewari, Physics Letters A 185, 139 (1994).
[8] P. G. Kwiat, A. G. White, J. R. Mitchell, O. Nairz, G. Weihs, H. Weinfurter, and A. Zeilinger, Phys. Rev. Lett. 83, 4725 (1999).
[9] O. Hosten, M. T. Rakher, J. T. Barreiro, N. A. Peter, and P. G. Kwiat, Nature 439, 949 (2006).
[10] T.-G. Noh, Phys. Rev. Lett. 103, 230501 (2009).
[11] D. Gabor, Nature 161, 777 (1948).