Modification of “Counterfactual communication protocols” which makes them truly counterfactual

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Possibility to communicate between spatially separated regions, without even a single photon passing between the two parties, is an amazing quantum phenomenon. The possibility of transmitting one value of a bit in such a way, the interaction-free measurement, was known for quarter of a century. The protocols of full communication, including transmitting unknown quantum states were proposed only few years ago, but it was shown that in all these protocols the particle was leaving a weak trace in the transmission channel, the trace larger than the trace left by a single particle passing through the channel. This made the claim of counterfactuality of these protocols at best controversial. However, a simple modification of these recent protocols eliminates the trace in the transmission channel and makes all these protocols truly counterfactual.

I. INTRODUCTION

The beginning of counterfactual communication was when Penrose [1] coined the term “counterfactuals” for describing quantum interaction-free measurements (IFM) [2]. The idea was developed to counterfactual cryptography [3], to counterfactual computation [4], to counterfactul computaion for all outcomes [5], and then to counterfactual communication [6]. More research about counterfactual protocols was done [7–14], and even a new kind of teleportation [15] which required no prior entanglement, no classical channel and no particles traveling between the parties was proposed [16, 17]. One of us, LV, although being a co-author of the original work [2] criticised many counterfactual protocols as being not counterfactual [18–22]. He showed that while the original IFM and all other protocols including counterfactual cryptography relying on communication of only one value of a bit were indeed counterfactual, the protocols for full communication and computation with two values of a bit were not counterfactual. In fact, he also thought that these tasks cannot be done in a counterfactual manner, but it turned out to be a mistake. In this Letter we present a simple modification of theses protocols which makes them fully counterfactual.

The basic definition of counterfactual communication is communication without particles in the transmission channel. It is enough that (counterfactually) the particles could have been in the channel, and/or they were in the channel in runs which were discarded in the communication protocol. The controversy about counterfactuality of the protocols was about definition of “particles being in the transmission channel”. The authors considering the protocols as counterfactual relied on classical reasoning: if the particle could not pass through the channel, it was not there. Vaidman claimed that one cannot use classical argumentation for discussing quantum particles and suggested the weak trace definition. When a particle passes through a channel it always slightly changes the quantum state of the channel, it leaves a weak trace. If in the communication protocol the trace left in the transmission channel is of the order (or larger) than the trace left by a passing single particle, then, by definition [24], the particle was in the channel and thus the protocol is not counterfactual.

The two-state vector formalism (TSVF) [25] provides a very simple way to find out when the trace is present: If there is an overlap of the forward and backward evolving states in the channel, then local interactions operators in the channel do not vanish and, therefore, the particle leaves a weak trace in the channel. Thus, by definition, the particle was present in the channel, i.e. the protocol is not counterfactual.

The basic counterfactual protocol, the IFM, is shown on Fig. 1. The photon in tuned Mach-Zehnder interferometer cannot reach detector D when there is nothing disturbing the photons inside the interferometer. It can click when we place an object in one arm of the interferometer. Considering everything to the left of the line I as the place of Alice, everything to the right of line II as the place of Bob, and everything between lines I and II as the transmission channel, the IFM is a counterfactual communication of a single value of a bit. Presence of a shutter on Bob’s cite we define as 1 and absence as 0. For value 1, Alice sends a single photon and she has a chance to get the click in D. Then she knows the bit and we can also claim that no particle was in the transmission channel. One argument (which we do not accept as legitimate) is that if it would be in the channel, we would not be able to get the click in D. But there is also another argument which we do find decisive: after performing the protocol, no trace is left in the transmission channel, see

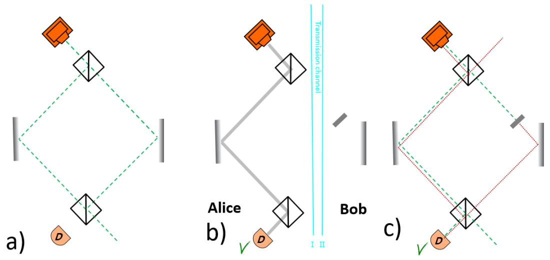

FIG. 1: Counterfactual detection of the presence of the shutter. a) The interferometer is tuned in such a way that detector D never clicks if the paths are free. b) Alice knows that Bob chose bit 1 (blocked the path) when she observes the click in D. Gray thick line shows the trace left by the photon. It does not present in the transmission channel. c) Forward and backward evolving wave function are shown. Places of their overlap shows, without calculation, where the photon leaves the weak trace.

Fig. 1b. This can be easily seen from the fact that at no point of the channel there is an overlap of the forward and backward evolving states, Fig. 1c.

The next ingredient of counterfactual protocols is transmitting bit 0, corresponding to the absence of the shutter. This apparently can be achieved using nested Mach-Zehnder interferometer, Fig. 2. The inner interferometer is tuned to destructive interference toward the final beam splitter of the external interferometer, Fig. 2a. The nested interferometer is also tuned such that the photon cannot reach detector D when arm A is blocked, Fig. 2b. It can reach detector D when nothing is blocked inside the interferometer. Thus, when Alice sends a single photon and it is detected in D, she knows that Bob did not put the shutter in arm A. Using classical physics approach, Alice also might claim that this was an event of counterfactual communication. The photon could not have been in arm A because photons entering inner interferometer could not reach detector D.

Although the photon could not pass through A, it left a significant trace there, Fig. 2c. The same trace as in C, where everyone agrees about the presence of the photon. Both in C and in A (and also in B) there is an overlap of the forward and backward evolving states, Fig. 2d.

To correct the protocol for detecting absence of the shutter we modify it such that it becomes counterfactual not only according to illegitimate classical argument, but also according to the quantum "no trace" criterion. The scheme is presented in Fig. 3. It is essentially two interferometers of Fig. 2. connected by a double-sided mirror. The inner interferometers are tuned, as before, to destructive interference toward the path of the external interferometer, Fig. 3a. The second requirement is not for each segment, but for the two together. The whole interferometer is tuned such that when both inner interferometers have blocked arms A, we get destructive interference toward detector D, Fig. 3b. So again, since it is arranged that there are only two options, either the two arms A blocked, or the two arms open, the click in D tells us that both are open. Alice knows that shutters are absent.

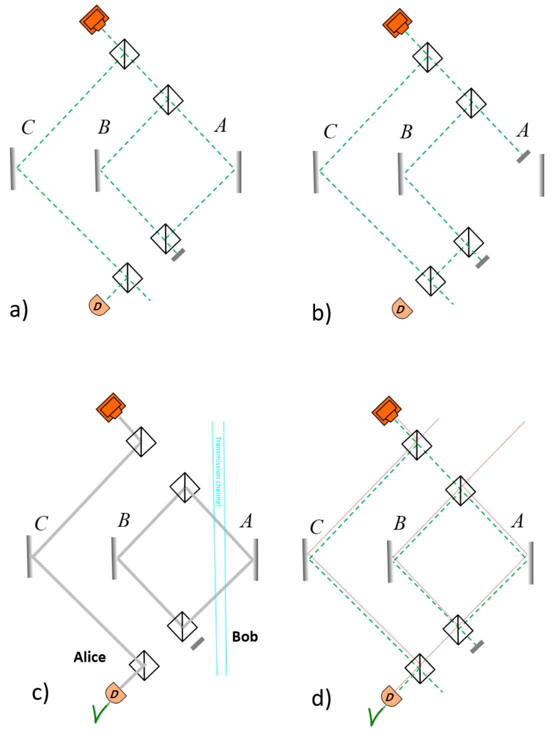

FIG. 2: Counterfactual detection of the absence of the shutter. a) The inner interferometer is tuned to destructive interference toward the continuation in the large interfereometer. b) The whole interferometer is tuned such that when arm A is blocked, detector D cannot click. c) There is a trace in arm C and inside the inner interferometer. In particular, there is a trace in the transmission channel which contradicts counterfactuality of the protocol. d) The overlap of the forward and the backward evolving waves explains the weak trace in the interferometer.

Classical argument tells us that the particle was not in arms A since photons entering inner interferometer cannot reach Alice's detector. More importantly, the trace criteria tells us that the photon was not in arms A. There is no need for calculations, we can see from Fig. 3c that the forward and backward evolving wave functions do not overlap in arms A and therefore, there is no trace in the transmission channel, Fig. 3d. We can safely claim that this setup is a counterfactual communication of bit 0.

One might note that the trace is not exactly zero in the transmission channel as in the case of communication of bit 1. Since always there is some interaction, some decoherence of the photon is present and we never get perfect destructive interference. Thus, there is a tiny leakage of the forward evolving wave toward the lower interferometer and of the backward evolving wave toward the upper interferometer, creating some overlap of the

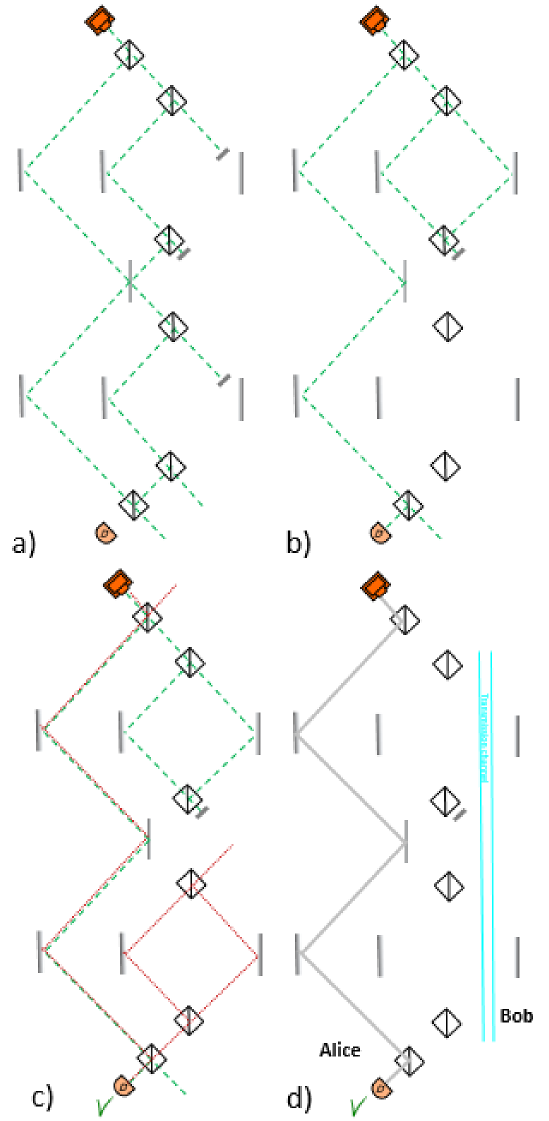

FIG. 3: Modified bit 0 counterfactual communication. a),b) describe the tuning of the interferometer: a) shows forward evolving wave function with the shutters and b) without the shutters; the whole interferometer is tuned such that when arms A are blocked, detector D cannot click. c) Forward and backward evolving states which explain the weak trace shown in d), in particular, there is no trace in the transmission channel.

forward and the backward evolving wave functions and, therefore, some trace in the transmission channel. However, this trace is much smaller than the trace of a single particle passing through the channel and thus, according to the weak trace criterion, it should be neglected.

The scheme for communication of bit 1 and the scheme for communication of bit 0 presented above are not the same, so we do not have yet a counterfactual communication protocols for all values of the bit. The ingenious combination of the two with help of quantum Zeno effect presented in [5, 6] provides the counterfactual communication protocol. The original proposal includes the chain of external interferometers, each one with a chain of inner interferometers. It is a very reliable communication protocol, it succeeds with probability very close to 1. The probability of the failure (loosing the photon or giving erroneous outcome) goes to zero with increasing the number of elements in the chains of the interferometer.

As mentioned above, the problem is that while the case with shutters is unquestionably counterfactual, the case without shutters is counterfactual only according to the naive classical argument: all particles passing to Bob's territory through the transmission channel could not reach Alice's detector where it was post-selected. Nevertheless, during the process, a weak trace is left in the transmission channel and it is larger than the trace of a single particle passing from Alice to Bob. One can perform exact calculations [21], but it could be seen just from drawing forward and backward evolving states, they overlap in the communication channel, see one element of the external chain in Fig. 4a. The weak trace is shown in Fig. 4b.

The simple correction method discussed above works here too. We just double each element of the chain of external interferometers connecting them with the two-sided mirror, Fig. 4c. When Bob places all shutters in, the protocol works as before the modification except for doubling the probability of losing the photon which is not a problem since it is very small. When Bob does not put the shutters, the communication happens exactly as before (given ideal mirrors). Again, there is no need for exact calculation. There is no overlap of the forward and backward evolving wave functions in the transmission channel, Fig. 4c. Thus, in the modified device, there is no trace in the transmission channel, Fig. 4d. At least, there is no trace of the order of the trace left by a particle passing through the channel. Indeed, the weak value of local operators in the transmission channel vanish, and therefore no trace of the first order in the interaction coupling of the photon with the channel is present.

Considering the shutter as a quantum computer performing calculation of a binary function of a binary input provides a method for counterfactual computation for all possible variables. The protocol [5] with this simple modification archives the task. And it is definitely a feasible task. The large interferometer with the chain of the units of the form presented in Fig. 4c. is not needed. Just three coupled optical cavities with two high-reflectivity beam splitter with one of them convertible into a two-sided mirror. Essentially the same experiment that has been performed, only the opening of the first beamsplitter happening after twice the time it was done originally. The same is true for the setup described in [6] and other variations.

Does it contradict the general limitation on counterfactual communication derived by Mitchison and Jozsa [26]? No, we do not have here a single (counterfactual) operation of the computer. We need multiple identical com-

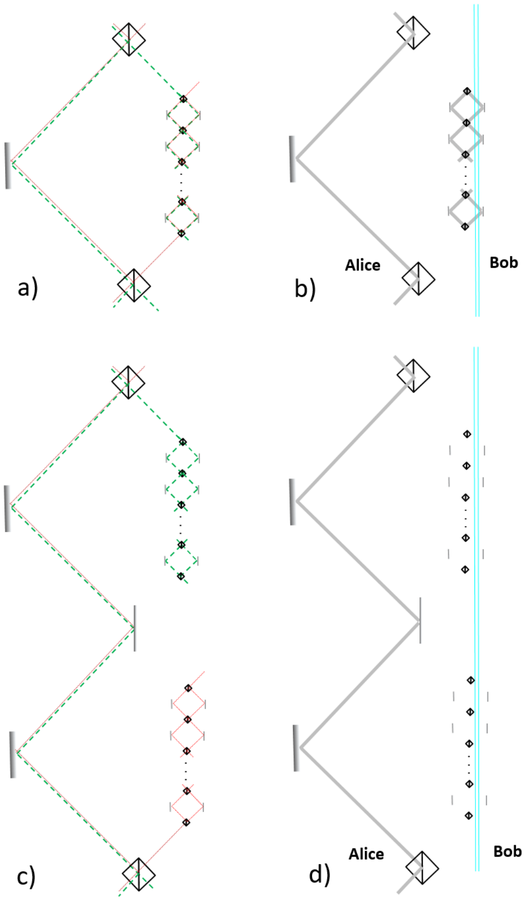

FIG. 4: a-b) One element of the chain of interferometers according to the old proposal for counterfactual communication. a) Forward and backward evolving states, b) the weak trace. c-d) The same for the modified element of the chain of the counterfactual protocol. There is no trace in the communication channel.

puters or the same computer interrogated many times.

The protocol of counterfactual communication of classical information explained above can be generalised to transmitting an arbitrary quantum state as explained in [16, 17, 22]. It is a quantum state of multiple shutters: superposition of the state when all block their paths A with the state when they all are outside the interferometer.

Counterfactual transfer of a quantum state looks like an improved version of quantum teleportation [15]: there is no need for preparation of a quantum entangled particles and nothing is transmitted between Alice and Bob, neither quantum particles, nor classical information. However, it does not have a practical advantage. The method requires multiple quantum channels to be build and/or multiple operations in time to be (counterfactually) performed. Also, it has a conceptual weakness. Given ideal devices, telepotation always succeeds, while counterfactual transmission succeeds only with probability arbitrary close to 1, but not 1.

Communication without particles moving in the transmission channel, and, especially transmission of a quantum state without presence of any particle in the transmission channel is a bizarre feature of quantum theory. It tells us that quantum theory must have some kind of action at a distance. One of us, LV, wants to mention that there is a way to escape action at a distance for the price of accepting existing multiple parallel worlds [27]. The physical intuition that nothing can happen without causal local action can be restored by applying physical intuition to all worlds together. The tiny probability of the failure of the protocol corresponds to existence of numerous other worlds in which the photon did pass through the channel.

Another consistent approach is not to ask where was the photon inside the interferometer. Analysis of the evolution of the forward evolving wave function (which passes through the transmission channel) explains all observable results. Still, operational meaning of quantum particles as leaving trace where they pass is a helpful feature describing quantum systems, especially of pre- and postselected quantum systems. It is useful and important to investigate the limits of classical description of our quantum world.

There were several experiments performing protocol for counterfactual communication which are not counterfactual according to the criterion of the weak trace in the transmission channel [5, 6, 28–30]. It will be of interest to repeat these experiments with the modification proposed here. Even more interesting, although much more challenging, is to experimentally compare between the weak traces left by the particle in the transmission channel in the original and in the modified schemes of counterfactual communication.

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