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STOCHASTIC TRANSFER OF A CLASSICAL INFORMATION THROUGHT QUANTUM CHANNELS USING THE QUANTUM PROBABILISTIC TELPORTATION PROTOCOL

Summary. Nonlocality of real world on the quantum level seems to be widely accepted fact today. Basing on this nonlocality several theoretic scenarios for teleporting a general quantum states are being presented, the simplest among them have been experimentally demonstrated as well. Although on the quantum level the information is transferred with superluminal speed the extraction of it onto the classical level obligatory requires an amount of classical information that has to be sent through classical channel. The present note discusses the possibility of transferring classical bits using quantum channels only for this purpose.

Keywords: probabilistic quantum teleportation

STOCHASTYCZNY TRANSFER INFORMACJI KLASYCZNEJ PRZEZ KANAŁ KWANTOWY PRZY UŻYCIU PROBABILISTYCZNEGO PROTOKOŁU TELEPORTACJI KWANTOWEJ

Streszczenie. Nielokalność świata na poziomie kwantowym wydaje się być zjawiskiem ogólnie zaakceptowanym. Opierając się na tej nielokalności zaproponowano szereg teoretycznych scenariuszy teleportacji dowolnych stanów kwantowych, a niektóre z nich nawet doczekały się eksperymentalnych implementacji. Jakkolwiek na poziomie kwantowym informacja jest transferowana z prędkością ponadświetlną, to jednak aby ją wydobyć do świata klasycznego, należy przesłać w kanale klasycznym dodatkową porcję informacji klasycznej. W pracy dyskutuje się możliwość transferu klasycznej informacji używając wyłącznie kanału kwantowego.

Słowa kluczowe: probabilistyczna teleportacja kwantowa

1. Introduction

In nonrelativistic quantum mechanics the term "nonlocality" refers to an apparent failure of a certain relativity-theory-based paradigm known as locality assumption [4, 5, 29, 34, 35, 6]. This paradigm says: there is no information about which experiment is freely chosen and performed in one space-time region available in a second space-time region unless a point travelling at the speed of light (or less) can reach the second region from the first. This assumption seems to be valid in relativistic classical physics. The powerful argument in flavour is that assuming opposite there do exists a Lorentz frame in which observer can detect a signal before it was sent, evident absurd!

Yet quantum theory permits the existence of certain experiments in which this locality assumption seems to fails. Einstein called the faster-than-light effects evidently entailed by conventional (Copenhagen) quantum theory "spooky action at a distance" [16].

The simplest of the experiments pertinent to this issue involve two measurements performed in two space-time regions that lie so far apart that nothing travelling at the speed of light or less can pass from either of these two regions to the other. The experimental arrangements are such that an experimenter in each region is able to choose between two alternative possible measurements. The locality assumption then demands, for each region, that the truth of statements exclusively about the outcomes of the possible measurements performed in that region be independent of which experiment is "freely chosen" in the other (faraway) region. The first actual experiment exhibiting these features was carried out by Aspect, Grangier, and Roger [1, 3, 15]. Dozens of other such experiments have been carried out since and the validity of the quantum predictions appears to be verified [22, 14].

The significance of this nonlocality property of quantum theory is clouded by several considerations. The first is that although the conventional quantum precepts do appear to entail the need for some sort of sub rose, behind-the-scenes, faster-than-light transfer of information this effect cannot be used to send a superluminal signal: no one can use this effect to transfer, superluminally, information that he or she possesses to a faraway region. This limitation on signal velocity, together with other relativistic features of the actually verifiable predictions of the theory, allows relativistic quantum field theory to be called "relativistic" in spite of the apparently entailed faster-than-light transfer of information. It might seem contradictory to assert first that locality fails, and hence that information about which experiment is freely chosen and performed in a first region is present in a second region, yet then to assert that the experimenter in the first region cannot use this feature to send information to a colleague in the second region. The resolution of the puzzle is that the dependence of faraway measurable properties on the choice made by the nearby experimenter arises only via nature's choice of the outcome of the nearby experiment. The faraway observer, lacking all knowledge about which outcome occurs in the sender's region, must treat that outcome as unknown. This leads to a quantum theoretical averaging over these outcomes that exactly eliminates all dependence upon the sender's free choice of anything that the receiving colleague can observe [36, 22].

As an example let us consider the well known EPR [16] –like pair of qubits the state of which is given by

$$|\psi\rangle = \alpha|00\rangle + \beta|11\rangle \text{ where } |\alpha|^2 + |\beta|^2 = 1, \tag{1}$$

and according to laws of quantum mechanics: if Alice is measuring a state (of being in her disposal first qubit) she obtains the result $|0\rangle$ with probability $|\alpha|^2$ and respectively $|1\rangle$ with probability $|\beta|^2$.

On the other hand, her partner called traditionally Bob, being located in faraway region is not familiar with results of her measurement and is doing his own measurements of state of his qubit. Then, with probability $|\alpha|^2$ he obtains result $|0\rangle$ and with probability $|\beta|^2$ the result $|1\rangle$. Thus the results of Bob measurements are the same as that of Alice. Even in the situation in which Alice and Bob are sharing initially a large reservoir consisting of pairs of qubits prepared in the state (1.1) Bob will be not able to answer a very simple question whether Alice in her laboratory is doing something or not. To see this we have, according to quantum mechanical rules, to compute the reduced density matrix by averaging over possible outcomes that Alice obtains in her laboratory of the pure state (1.1).

The density matrix ρ corresponding to the state $|\psi\rangle$ has the following nonzero matrix elements:

$$\rho = |\psi\rangle\langle\psi| = |\alpha|^2 |00\rangle\langle 0^*0^*| + \alpha\beta^* |00\rangle\langle 1^*1^*| + \alpha^*\beta|11\rangle\langle 0^*0^*| + |\beta|^2|11\rangle\langle 1^*1^*|, \tag{2}$$

where α^* denotes the complex conjugation of α.

By simple calculations the corresponding reduced density matrix ρ_B has the form:

$$\rho_B = \begin{bmatrix} |\alpha|^2 & 0 \\ 0 & |\beta|^2 \end{bmatrix} |\psi\rangle\langle\psi| = |\alpha|^2|0\rangle\langle 0| + |\beta|^2|1\rangle\langle 1|. \tag{3}$$

Thus, whatever the Alice is doing on her side the statistics of Bob's outcomes is described by the density matrix ρ_B and any kind of non-local communication in between Alice and Bob is impossible.

The organization of this note is the following: in the next Section 2, we put on the rigorous ground the (rather well known) most general form of "no signalling principle" and in this way we show that the only an extremely tiny and narrow opportunities for such kind of signalling with the use either of nonlinear operations or with the use of dissipating information operations remain still in this game.

Some ideas for constructing a quantum mechanical device which dissipates information and based on the deformation of the standard teleportation circuits will be presented in Section 3.

2. Why and when the superluminal signaling is impossible?

It is conventional wisdom telling us that there is peaceful coexistence in Nature in between standard causality and quantum mechanical nonlocality, the coexistence which in particular prevents to transfer any amount of classical information with superluminal speed. However a rigorous exposition of this dogma is rather hard to find in full generality in literature, although the whole story begun already in sixties [25] and evolved slowly during decades and finally at present can be formulated in a very general context [19, 8]. It is the aim of the present section to provide a quick proof of a very general result of this type. As a byproduct of our reasoning it will become rather clear that still there do exists a very narrow space (not excluded by our considerations) for performing superluminal signalization [26].

So, let A and B be two quantum systems with theirs corresponding Hilbert spaces of states denoted as H_A and respectively H_B. The states of the composite system A+B are described by density matrices on the space $H_A \otimes H_B$ and the set of all of them will be denoted as $E(H_A \otimes H_B)$.For more information on density matrices see i.e. [8, 12, 13, 35].

A linear maps acting on the spaces of density operators will be denoted as Θ and will be called admissible physical operations. In particular admissible physical operations are trace preserving. The space of all admissible operations will be denoted by $A(H)$.

From the very definition of $A(H)$ it follows that any kind of quantum mechanical measurement, including the best known, projective one of von Neumann type, or the noisy measurements described by complete POVM are allowed operations. Any positive, trace preserving operations belong to the space $A(H)$.

A state $\rho \in E(H_A \otimes H_B)$ allows standard superluminal communications in between subsystem A and B iff there exists at least two different admissible operations on H_A such that the corresponding reduced density matrices (defined as a partial tracing on H_A of the state ρ) are different.

Let us note that if the state $\rho \in E(H_A \otimes H_B)$ is separable then the superluminal signaling is impossible.

Proof:

From the definition of separability it follows that

$$\rho = \sum_{\alpha} c_\alpha \rho_A^\alpha \otimes \rho_B^\alpha, \rho_A \in E(H_A), \rho_B \in E(H_B). \quad (4)$$

Therefore, for any $\Theta_A \in A(H_A)$ we have

$$\rho^B = Tr_{H_A}((\Theta_A \otimes I)\rho) = \sum_\alpha c_\alpha Tr(\Theta_A(\rho_A^\alpha))\rho_B^\alpha = \sum_\alpha c_\alpha \rho_B^\alpha \,. \tag{5}$$

Theorem 2.1

Let A and B be any quantum mechanical systems. Then there is no possibility for superluminal communications for any state of composite system.

Proof:

The partial trace operations is trace preserving operations, therefore taking any $\rho \in E(H_A \otimes H_B)$ and any $\Theta_A^1, \Theta_A^2 \in A(H_A)$ we can construct the corresponding density reduced matrices

$$\begin{aligned} \rho_B^{(1)} &= Tr_{H_A}((\Theta_A^1 \otimes I_B)\rho) \\ \rho_B^{(2)} &= Tr_{H_A}((\Theta_A^2 \otimes I_B)\rho) \end{aligned}, \tag{6}$$

where $Tr_{H_A}(\cdot)$ means the partial trace with respect to the first factor H_A. For more infrmation on his see i.e. [12, 13, 35].

Taking any arbitrary observable F_B (i.e. linear hermitean operator acting on H_B) we have

$$\langle I_A \otimes F_B \rangle_\rho = Tr_{H_A \otimes H_B}((I_A \otimes F_B)\rho) = Tr_{H_B} F_B(Tr_{H_A}\rho) \,. \tag{7}$$

But noting that by the trace preservation property of the partial trace operation

$$Tr_{H_A}((\Theta_A^1 \otimes I_B)\rho) = Tr((\Theta_A^2 \otimes I_B)\rho) = Tr_{H_A}(\rho) \,, \tag{8}$$

we can conclude

$$\langle I_A \otimes F_B \rangle_\rho = \langle F_B \rangle_{\rho_B^1} = \langle F_B \rangle_{\rho_B^2} \,, \tag{9}$$

for any $\Theta_A^1, \Theta_A^2 \in A(H_A)$ and any observable F_B. Thus, there is no measurement in B which can differentiate in between the situations in which different standard allowed operations were performed on the part A of the system.

Thus the only chance for supplying superluminal communication is to perform some sorts of nonlinear operations on the system or to perform i.e. incomplete measurements on the system or more generally an operation which do not preserve the trace. However such possibilities looks to be rather exotic from the point of view of the generic quantum theory and will be not discussed in the present note.

For further use we note also the following technical lemma

Lemma 2.2

Let $\rho \in E(C^8)$ be of the form

$$\rho = \sum_{\substack{i,j,k=0,1 \\ i^*,j^*,k^*=0,1}} \rho^{i,j,k|i^*,j^*,k^*} \left| ijk \right\rangle \left\langle i^* j^* k^* \right| \,. \tag{10}$$

Then the following formulas are valid:

$$1.: \ \rho_{(1,2)} = Tr_{(1,2)}\rho = \sum_{\substack{k=0,1 \\ k^*=0,1}} \rho_{(1,2)}^{k|k^*} |k\rangle\langle k^*|, \text{ where } \rho_{(1,2)}^{k|k^*} = \sum_{i,j=0,1} \rho^{ijk|ijk^*}, \tag{11}$$

$$2.: \ \rho_{(2)} = Tr_{(2)}\rho = \sum_{\substack{i,k=0,1 \\ i^*,k^*=0,1}} \rho_{(2)}^{ik|i^*k^*} |ik\rangle\langle i^*k^*|, \text{ where } \rho_{(2)}^{ik|i^*k^*} = \sum_{j=0,1} \rho^{ijk|i^*jk^*}. \tag{12}$$

3. Modification of teleportation circuit

Theorem 2.1 of previous section definitely excludes the possibility of supplying the device which can be called quantum telegraph by the use of the standard deterministic teleportation protocols. In particular, using the explicite form of Lemma 2.2 the possibility of sending classical 0 or 1 bits by the standard [7] two-bit teleportation protocol can be excluded by simple calculations.

However there is still some narrow window for performing some thing very close to the concept of quantum telegraph. This can be achieved by a suitable deformation of the standard teleportation circuits and the use of a series of transfer which might do not have fidelity equal to one. This idea is being illustrated by considerations presented below.

Fig. 1 depicts a changed version of one-bit teleportation protocol [27]. We use additional real rotation gate to modify the entanglement in the part A. Similar gate can be added to the part B, where Alice entangle first qubit with the second one. The second possible change is the two qubit NOT gate. Instead of use typical CNOT two-qubit gate where the second qubit is changed when the first is in state ‘one’ we use CNOT gate where the second qubit is changed when the first qubit is in the state ‘zero’. We also add two Toffoli gates in the part B. These gates allow important change in the amplitudes distribution.

We also introduce measurement state for Bob’s qubit. The main assumption for our version of the probabilistic teleportation protocol is the fact that we teleport one know state by Alice and Bob and the measurement operation which is done by Alice (dotted block A) is optional.

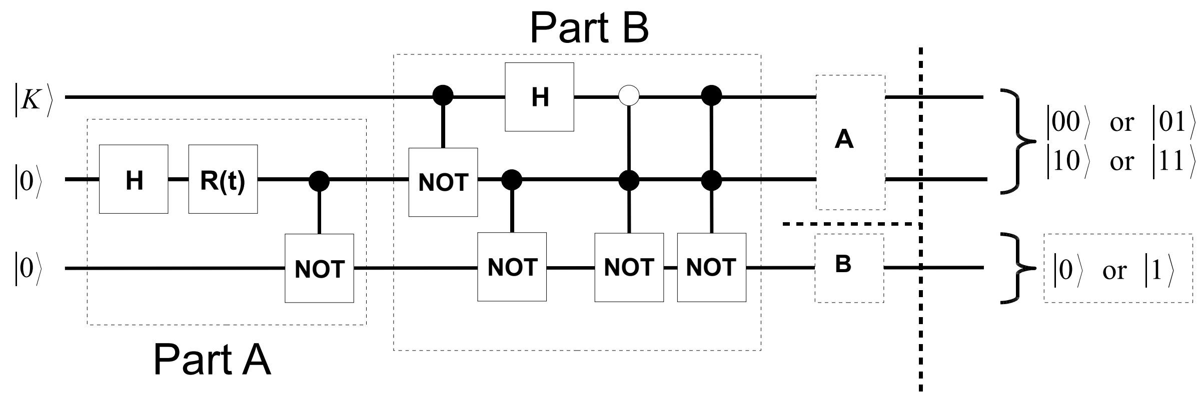

Fig. 1. Quantum circuit for the probabilistic teleportation
Rys .1. Obwód kwantowy do teleportacji probabilistycznej

The use of mentioned circuit can be expressed with the following algorithm. In the first step Bob and Alice prepare a set of n three qubit systems. For all n systems Alice and Bob prepare the entanglement between the second and third qubit with the skew given by the theta value. As in deterministic version of teleportation protocol Bob possess only the third qubit and Alice possess the first and the second one. The proposed algorithm has following steps for Alice:

- Alice and Bob select the value of theta parameter and one state denoted by $|K\rangle$,
- Alice prepares n three-qubit system as is depicted on the Fig.1 (using operations in Part A and B)
- From every three-qubit systems Bob takes the third qubit. Additionally Alice informs Bob, that k qubits from n represent one group,
- if Alice sends the classical state zero then she do not execute the measurement procedure,
- if Alice sends the classical state one then she execute the measurement procedure.

Bob realises following steps:

- Bob measures third qubit in one of k group,
- if Bob obtain the probability distribution which is similar to classical state one then it is possible to assume that Bob obtained classical state zero,
- if the probability distribution is similar to the classical state one then Bob can assume that he obtained the classical state one.

Presented algorithm can be easily implemented with the quantum computing simulator [30,31].

3.1. Numerical example

Let us consider circuit from Fig. 1 where first CNOT gate is a typical controlled-not i.e. the Not gate is executed when the first qubit is in the state one. For $\Theta = 0.2$ and teleportation of the state $1/\sqrt{2}(|0\rangle+|1\rangle)$ the state of whole circuit before Alice's measurement and before Toffoli gate application and after has following form

$$\begin{matrix} 0.276266 & |000\rangle \\ 0.416746 & |001\rangle \\ 0.416746 & |010\rangle \\ 0.276266 & |011\rangle \\ 0.276266 & |100\rangle \\ -0.416746 & |101\rangle \\ 0.416746 & |110\rangle \\ -0.276266 & |111\rangle \end{matrix}, \quad \textit{after amplitudes swap} \quad \begin{matrix} 0.276266 & |000\rangle \\ 0.416746 & |001\rangle \\ 0.276266 & |010\rangle \\ 0.416746 & |011\rangle \\ 0.276266 & |100\rangle \\ -0.416746 & |101\rangle \\ -0.276266 & |110\rangle \\ 0.416746 & |111\rangle \end{matrix}. \tag{13}$$

Probability of measurement zero or one by Bob in both cases is still the same $P(0)=0.5$ and $P(1)=0.5$. However after Alice measurement operation the circuit's state can be depicted in following way (states for all four results: $|00\rangle$, $|01\rangle$, $|10\rangle$, $|11\rangle$)

$$\begin{matrix} 0.552531 & |000\rangle \\ 0.833492 & |001\rangle \\ 0.0 & |010\rangle \\ 0.0 & |011\rangle \\ 0.0 & |100\rangle \\ 0.0 & |101\rangle \\ 0.0 & |110\rangle \\ 0.0 & |111\rangle \end{matrix} \; or \; \begin{matrix} 0.0 & |000\rangle \\ 0.0 & |001\rangle \\ 0.552531 & |010\rangle \\ 0.833492 & |011\rangle \\ 0.0 & |100\rangle \\ 0.0 & |101\rangle \\ 0.0 & |110\rangle \\ 0.0 & |111\rangle \end{matrix} \; or \; \begin{matrix} 0.0 & |000\rangle \\ 0.0 & |001\rangle \\ 0.0 & |010\rangle \\ 0.0 & |011\rangle \\ 0.552531 & |100\rangle \\ 0.833492 & |101\rangle \\ 0.0 & |110\rangle \\ 0.0 & |111\rangle \end{matrix} \; or \; \begin{matrix} 0.0 & |000\rangle \\ 0.0 & |001\rangle \\ 0.0 & |010\rangle \\ 0.0 & |011\rangle \\ 0.0 & |100\rangle \\ 0.0 & |101\rangle \\ 0.552531 & |110\rangle \\ 0.833492 & |111\rangle \end{matrix} \tag{14}$$

In each result because of application the Toffoli gates we have proper probability amplitude distribution. Therefore, in each result Bob after Alice measurement obtain a different probability values when he measure own qubit. In upper case Bob obtains $P(0)\approx 0.30529$ and $P(1)\approx 0.694709$.

4. Conclusions

It is a conventional wisdom telling us that although there do exist some nontrivial correlations between space-like separated parties of quantum systems (providing that global state of the system is entangled one) they do not allow superluminal communications in between these parties. The existence of such quantum correlations is experimentally verified by many experimental groups at present by detecting the breakdown of the famous Bell inequalities. However it is hardly to find sufficiently simple and exhaustive mathematical proofs of the mentioned wisdom and this note fills this gap. The proof presented in Section 2, Theorem 2.3 definitely excludes a possibility of any kind of superluminal communications providing the attempts for them are performed by standard linear and trace preserving operations. As a particular application of our main result we have disproved as physically impossible task a recently discussed in the literature idea to use kind of possible deformations of a standard teleportation circuits to achieve a sort of a probabilistic superluminal signaling. A general theorem of this sort will be presented in a separate publication.

However our proof is not excluding the possible use of (rather nonstandard) nonlinear and/or information dissipating operations for achieving such fantastic form of communication as the superluminal communication would be.

In conclusion, presented numerical implementations of stochastic transfer information protocol confirms correctness of the scheme. In other words it is possible to obtain the probabilistic teleportation but only one state with modifying final amplitudes, however is must be stressed that success of probabilistic teleportation depends on the theta angle used to prepare no-maximally entanglement between Alice's and Bob's qubits. Nevertheless further work is still needed, especially with the other teleportation scheme.

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Omówienie

W artykule przedstawiono twierdzenie 2.1 wykluczające transmisję dowolnego stanu kwantowego przez protokół teleportacji kwantowej. To oznacza, iż bezpośrednie zastosowanie standardowych schematów teleportacji do superluminalnej komunikacji, gdzie transferowane będą dowolne stany kwantowe w sposób całkowicie deterministyczny, nie jest możliwe. Pozostają wobec tego protokoły probabilistyczne, niestety również i w tym przypadku podczas teleportacji dowolnych stanów rozkłady prawdopodobieństwa dążą do rozkładu 0.25/0.25/.025/0.25 dla czterech podstawowych wyników otrzymywanych przez Alicję, co oznacza, iż Bob ostatecznie będzie otrzymywał wartości zero bądź jeden z prawdopodobieństwem równym ½.

Z tych powodów zaproponowano pewną modyfikację (rys. 1) jednobitowego protokołu teleportacji kwantowej (24). Głównym elementem modyfikacji jest fakt zastosowania splątania o zmodyfikowanych amplitudach, co pozwala na zmianę rozkładu prawdopodobieństwa w finalnym stanie. Umożliwia to, za pomocą całej serii pomiarów wielu qubitów, po stronie

Boba, wykryć tylko, czy Alicja wykonała po swojej stronie operację pomiaru. Nie jest to całkowicie poprawny schemat teleportacji, ponieważ otrzymany stan finalny różni się od początkowego, inaczej mówiąc, miara Fidelity pomiędzy stanem początkowym i teleportowanym jest różna od jedności.

Jednym z najbardziej ważnych zagadnień związanych z tym protokołem byłaby naturalnie jego realizacja fizyczna i możliwość zastosowania jako kwantowego telegrafu transferującego klasyczną informację z superluminalną prędkością w kanale kwantowym.

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