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Remote interactions on two distributed quantum systems: nonlocal unambiguous quantum-state discrimination*

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Remote quantum-state discrimination is a critical step for the implementation of quantum communication network and distributed quantum computation. We present a protocol for remotely implementing the unambiguous discrimination between nonorthogonal states using quantum entanglements, local operations, and classical communications. This protocol consists of a remote generalized measurement described by a positive operator valued measurement (POVM). We explicitly construct the required remote POVM. The remote POVM can be realized by performing a nonlocal controlled-rotation operation on two spatially separated qubits, one is an ancillary qubit and the other is the qubit which is encoded by two nonorthogonal states to be distinguished, and a conventional local Von Neumann orthogonal measurement on the ancilla. The particular pair of states that can be remotely and unambiguously distinguished is specified by the state of the ancilla. The probability of successful discrimination is not optimal for all admissible pairs. However, for some subset it can be very close to an optimal value in an ordinary local POVM.

Keywords: remote quantum-state discrimination, positive operator valued measure, nonlocal controlled-rotation, entanglement

PACC: 0365, 4250

1. Introduction

Quantum entanglement has no classical analogue and such a novel characteristic leads to many applications in quantum information science, e.g. teleportation,[1,2] dense coding,[3,4] quantum cryptography,[5,6] quantum computation,[7] and so on. These studies exploit the relation between quantum entanglement nonlocality and the structure of the Hilbert space. Although quantum entanglement has been a major research topic in the last decades, the nature of the relation between entanglement nonlocality and the properties of physical interactions is a fairly new subject. During the recent years it has been realized that entanglement can be used as a resource for implementing various types of remote interactions.[8−12] Optimal ways of generating entanglement by using a given interaction have been searched.[13]

On the other hand, the rapidly increasing interest in quantum information theory and its applications has resulted in a renewed interest in the theory of quantum measurement. Quantum measurement is an inevitable part of all quantum information processing tasks. Specific sets of quantum measurements are essential to optimal quantum-state estimation. Quantum measurements also represent the final step of any quantum computation. In many situations the choice of an optimal measurement depends on the task to be performed. For instance, in the case of quantum teleportation or quantum cryptography a central problem is the capability of discriminating among different outcomes. In general, these outcomes appear as nonorthogonal quantum states (lying in a space spanned by logical qubits), which can either stay close together or be located at widely separated places of a quantum network. Quantum mechanics forbids deterministic discrimination among nonorthogonal states. Nevertheless, the capability to distinguish nonorthogonal states unambiguously is an important primitive in quantum information and quantum communication. There are, in fact, two different optimal strategies developed to accomplish quantum-state discrimination (QSD) tasks. 'Minimum-error discrimination'

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(MD) seeks a 'best guess' on every trial, minimizing the rate of incorrect guess. Helstrom showed that[14] for the MD between two states, the optimal strategy could always be achieved by a (von Neumann) projective measurement. 'Unambiguous quantum-state discrimination' (UD), on the other hand, seeks to determine with certainty which state the system is in. This can be done only on some fraction of the trials. The others are termed 'inconclusive', and the optimal UD success rate cannot always be achieved with projective measurement. This issue has been first touched by Ivanovic[15] for the case of two equally probable nonorthogonal states. Peres[16] solved the problem of discrimination between two states in formulation with generalized measurements (or positive operator valued measurements (POVMs)). In Refs.[16, 17] the proposals involve the coupling of the original qubit to an ancillary particle. The ancilla evolves conditionally, depending on the state of the original system. The global system reaches a superposition of orthogonal conclusive and inconclusive states, which can be split up after a measurement on the ancilla. In the conclusive case, recognition of the original state is achieved by measuring σ_x. In Ref.[18] Jaeger and Shimony have shown that the same result can be obtained by extending the dimension of the accessible space, where extra dimensions play the role of the ancilla. In this case, inconclusive measurements are associated with measurements on the extra dimension component. Chefles and Barnett[19] have generalized Peres's solution to an arbitrary number of equally probable states which are related by a symmetry transformation. UD was already realized experimentally. The first experiment, designed for the discrimination between two linearly polarized states of light, was done by Huttner *et al.*[20] There have also been made some newer proposals of optical implementation.[21] The MD was demonstrated by Barnett and Riis.[22]

The actual state-distinguishing device for two known states depends on the two states, $|\psi\rangle_1$ and $|\psi\rangle_2$, two states that are 'hard wired' to the machine. Another approach is to supply the information about the states to be distinguished as quantum inputs. That is, one encodes the information about the states one wants to distinguish into a quantum state, which is then a kind of quantum program that is sent into the discriminator at the same time as the particle whose state is to be identified. The first device of this kind was proposed by Dušek and Buzek.[23] This device distinguishes the two states $\cos(\varphi/2)|0\rangle \pm \sin(\varphi/2)|1\rangle$, and the angle φ is encoded into a one-qubit state in a somewhat complicated way. In a series of recent studies Fiurášek *et al* [24] investigated a closely related programmable device that could perform a von Neumann projective measurement in any basis, the basis that is specified by the program. Sasaki and Carlini[25] developed a relevant device, which they called a quantum matching machine. Bergou and Hillery[26] proposed an approach to a programmable state discriminating machine in which the program was related in a simple way to the qubit states $|\psi\rangle_1$ and $|\psi\rangle_2$ that one is trying to distinguish. The original result in Ref.[26] was about unambiguous discrimination and about qubit date and program states. They have recently been extended to qudits by Hayashi *et al* both for optimum unambiguous discrimination[27] and for minimum error discrimination.[28]

However, all of the previous investigations are restricted to local quantum-state discrimination.

Physical implementation of quantum computation requires the coherent manipulation of a large number of qubits. To scale up the number of qubits in real physical systems, a particularly interesting approach is to connect individual physical setups together through some quantum communication channels and perform distributed quantum computation over all the nodes.[29] Such a quantum network approach has provided practical scaling methods for several promising candidate systems to implement quantum computation. For instance, in a trapped ion or cavity quantum electrodynamical (QED) system, the number of qubits inside an individual trap or cavity can be limited from some practical considerations, but the limitation can be overcome by wiring to those individual systems through photon connection.[30] To realize the distributed quantum computation, not only quantum state but also quantum operation has to be transferred between the nodes of the network efficiently. Implementation of remote QSD, which is a particular case of remote interaction, is a critical step for the implementation of quantum network and distributed quantum computation. Remote implementation of quantum measurements is more challenging than teleportation of quantum states.

In this paper we extend the protocol introduced in Ref.[23] to remote UD. We propose a protocol to implement the remote UD on a spatially separated quantum system using entanglements in addition to local operations and classical communications (LOCCs).

2. Unambiguous quantum-state discrimination and positive operator valued measurement

Unambiguous quantum-state discrimination among N states has $N+1$ outcomes: N possible conclusive results, and one inconclusive result. Since no projective measurement in an N-dimensional Hilbert space can have more than N outcomes, generalized measurements are required. POVM provides the most general physically realizable measurement in quantum mechanics.[31] A setup in which all possible POVMs of a single photon polarization state can be implemented easily by using linear optical elements has been presented by Ahnert and Payne.[32] A POVM is given by a set of positive definite Hermitian operators $\{F_i\}$, which in turn can be expressed in terms of a set of the so-call Kraus operators $\{M_i\}$, such that $F_i = M_i^+ M_i$ and for a POVM with n operators,

$$\sum_{i=1}^{n} M_i^+ M_i = \sum_{i=1}^{n} F_i = \boldsymbol{I}, \tag{1}$$

where $\boldsymbol{I}$ is the unit matrix. Suppose that a POVM described by measurement operators $\{M_i\}$ is performed on a quantum system in state $|\psi\rangle$. Then the probability of outcome i is given by $P(i) = \langle\psi|M_i^+ M_i|\psi\rangle$.

The Stinespring–Kraus theorem[31] relates any quantum operation realized on system B, which corresponds to a unitary transformation performed on a larger system $B + A$. In a similar way, a POVM performed on a quantum system B can be realized by entangling system B with ancillary system A via unitary evolution U. Postselection (projective measurement) of the ancilla induces an effective nonunitary transformation ε of original system $|\phi\rangle_B$, i.e.

$$\varepsilon[|\phi\rangle_B] = \mathrm{Tr}_A[U|\phi\rangle_B \otimes |\phi\rangle_A U^+], \tag{2}$$

where $|\phi\rangle_A$ is an appropriately chosen state of ancillary system A and Tr_A denotes a partial trace over ancilla A. By the appropriate design of the entangling unitary, this effective nonunitary transformation can turn an initially nonorthogonal set of states into a set of orthogonal states with a finite probability of success. The optimum strategy is the one that maximizes the average probability of success for this procedure.

The assignment $\varepsilon \rightarrowtail (U, |\phi\rangle_A)$ is one to many, because the dilation of the Hilbert space of system B can be performed in many different ways. However, if we fix transformation U, state $|\phi\rangle_A$ of ancillary system A controls and determines quantum operations that are going to be performed on system B. In this way one obtains a concept of a 'programmable quantum processor'[33] that takes as an input a data register (system B) and a program register (system A). Here the state of program register $|\phi\rangle_A$ encodes the operation $|\phi\rangle_B \rightarrow |\phi\rangle'_B = \varepsilon[|\phi\rangle_B]$ that is going to be performed on the data register. This pure quantum control can be realized without any intermediate intervention of an observer.

3. Nonlocal unambiguous quantum-state discrimination

Suppose that we want to discriminate remotely and unambiguously between two known nonorthogonal states.

Consider that Alice and Bob, who are localized in different space domains, are involved in the process. Alice possesses a device that is able to perform QSD locally, whereas Bob has a qubit that is encoded by two nonorthogonal states one want to distinguish. We can always choose such a basis that the following relationships hold:

$$\begin{aligned} |\phi_+\rangle_B &= \cos(\varphi/2)|0\rangle_B + \sin(\varphi/2)|1\rangle_B, \\ |\phi_-\rangle_B &= \cos(\varphi/2)|0\rangle_B - \sin(\varphi/2)|1\rangle_B, \end{aligned} \tag{3}$$

where the values of all φ are taken from the interval $(0, \pi)$ (suppose $|\sin(\varphi/2)| \leq |\cos(\varphi/2)|$); that is, we consider that all pairs of states in a real plane are located symmetrically around the state $|0\rangle_B$. Surely, any remote QSD can be implemented given enough shared entanglements and classical communications. Consider the case of single qubit, the remote QSD on Bob's qubit $|\phi_\pm\rangle_B$ can be accomplished by Bob teleporting his qubit $|\phi_\pm\rangle_B$ to Alice, Alice performing QSD locally on $|\phi_\pm\rangle_B$ and finally Alice teleporting Bob's qubit back to Bob. The resources needed for the two teleportation actions are two ebits (entanglement bits) and four cbits (classical bits). The 'double teleportation' procedure shown above is sufficient to implement any quantum evolution. The question is, however, whether so many resources are actually needed. A better way to achieve the remote UD is through the direct teleportation of quantum operation. We now see how Alice can assist Bob remotely to distinguish between the nonorthogonal states unambiguously by using one ebit and three cbits. In the

usual local procedure the ancilla is in the hands of Bob, here we will have the ancilla be with Alice. Further, we suppose that the ancillary qubit is allowed to be in an arbitrary pure state

$$|\phi\rangle_A = a|0\rangle_A + b|1\rangle_A. \quad (4)$$

In order to complete the above task, an ancillary ebit $|E\rangle_{ab} = 1/\sqrt{2}(|00\rangle + |11\rangle)_{ab}$ has to be prepared and shared by Alice with a and Bob with b. Thus the total input state reads

$$|\psi\rangle_{BAab} = |\phi_\pm\rangle_B|\phi\rangle_A|E\rangle_{ab}. \quad (5)$$

The realization of the remote POVM requires interaction U_{AB} between ancilla A and system B. Our first goal is to find how to construct this nonlocal transformation by using entanglements and LOCCs, when the ancilla is located far from Alice. Alice and Bob's strategies can be divided into the following steps.

(1) Alice performs a controlled-rotation gate

$$U_{aA} = |0\rangle_a\langle 0|_a \otimes [U_y(\theta)]_A + |1\rangle_a\langle 1|_a \otimes I_A \quad (6)$$

on qubits a and A, where

$$U_y(\theta) \equiv \exp(-\mathrm{i}\theta\sigma_y/2) = \begin{pmatrix} \cos(\theta/2) & -\sin(\theta/2) \\ \sin(\theta/2) & \cos(\theta 2) \end{pmatrix} \quad (7)$$

is the rotation operator about the y-axis through an arbitrary angle $\theta \in (0, \pi]$. Then she performs a σ_x measurement on qubit a and sends the result to Bob. Here one cbit has to be sent from Alice to Bob.

(2) Bob applies I_b or $(\sigma_z)_b$ to qubit b according to Alice's measurement result. The following state can be obtained:

$$|\psi\rangle_{BbA} = (1/2)|\phi_\pm\rangle_B\{|0\rangle_b[U_y(\theta)]_A + |1\rangle_b\}|\phi\rangle_A, \quad (8)$$

where we have discard qubit a.

(3) Bob performs a controlled-phase gate

$$U_{Bb} = |0\rangle_B\langle 0|_B \otimes (\sigma_x)_b + |1\rangle_B\langle 1|_B \otimes I_b \quad (9)$$

on qubits B and b. After this operation, the state $|\psi\rangle_{BbA}$ becomes

$$\begin{aligned} &(1/2)\cos(\varphi/2)|0\rangle_B\{|0\rangle_b + |1\rangle_b[U_y(\theta)]_A]\}|\phi\rangle_A \\ &\pm(1/2)\sin(\varphi/2)|1\rangle_B\{|0\rangle_b[U_y(\theta)]_A + |1\rangle_b\}|\phi\rangle_A. \end{aligned} \quad (10)$$

Then a σ_Z measurement on qubit b is made by Bob and the measurement result is communicated to Alice. Here one cbit has to be sent from Bob to Alice.

(4) As soon as Alice is informed of Bob's result, she can perform an appropriate unitary transformation (according to two possible results $|1\rangle_b$ and $|0\rangle_b$, the corresponding transformations are I_A and $[U_y(\theta)]_A$) on qubit A to obtain the state

$$\begin{aligned} |\psi\rangle_{BA} =& (1/2)\{\cos(\varphi/2)|0\rangle_B[U_y(\theta)]_A \pm \sin(\varphi/2)|1\rangle_B\}|\phi\rangle_A \\ =& (1/2)\cos(\varphi/2)|0\rangle_B\{[a\cos(\theta/2) - b\sin(\theta/2)]|0\rangle_A \\ &+ [a\sin(\theta/2) + b\cos(\theta/2)]|1\rangle_A\} \pm (1/2)\sin(\varphi/2)|1\rangle_B(a|0\rangle_A + b|1\rangle_A) \\ =& (1/2)\{[a\cos(\varphi/2)\cos(\theta/2) - b\cos(\varphi/2)\sin(\theta/2)]|00\rangle_{BA} \\ &+ [a\cos(\varphi/2)\sin(\theta/2) + b\cos(\varphi/2)\cos(\theta/2)]|01\rangle_{BA} \\ &\pm a\sin(\varphi/2)|10\rangle_{BA} \pm b\sin(\varphi/2)|11\rangle_{BA}\} \\ =& (1/2)U_{BA}|\phi_\pm\rangle_B|\phi\rangle_A, \end{aligned} \quad (11)$$

where

$$U_{BA} = |0\rangle_B\langle 0|_B \otimes [U_y(\theta)]_A + |1\rangle_B\langle 1|_B \otimes I_A \quad (12)$$

is a non-local controlled-rotation gate.

Thus the implementation of nonlocal unitary operation U_{AB} is completed. The implementation consumes one ebit represented by the state $|E\rangle_{ab}$ and one cbit in each direction to communicate the measurement outcomes.

If coefficients a and b in the state of ancilla are chosen such that

$$\begin{aligned} &[a\cos(\varphi/2)\cos(\theta/2) - b\cos(\varphi/2)\sin(\theta/2)] \\ &= \sin(\varphi/2)a = p/\sqrt{2}, \end{aligned} \quad (13)$$

then expression (11) is simplified into the from

$$\begin{aligned} &(1/2)U_{BA}|\phi_\pm\rangle_B|\phi\rangle_A \\ &= (1/2)[p(1/\sqrt{2})(|0\rangle_B \pm |1\rangle_B)|0\rangle_A \end{aligned}$$

$$+(C_1|0\rangle_B \pm C_2|1\rangle_B)|1\rangle_A]$$
$$= (1/2)(|0\rangle_A(M_0)_B|\phi_\pm\rangle_B + |1\rangle_A(M_1)_B|\phi_\pm\rangle_B), \quad (14)$$

where

$$C_1 = \sqrt{\cos^2(\varphi/2) - a^2\sin^2(\varphi/2)}$$

and

$$C_2 = b\sin(\varphi/2);$$

the measurement operators

$$M_0 = a\begin{pmatrix} \mathrm{tg}\,(\varphi/2) & 0 \\ 0 & 1 \end{pmatrix}$$

and

$$M_1 = \begin{pmatrix} \sqrt{1 - a^2\mathrm{tg}^2(\varphi/2)} & 0 \\ 0 & b \end{pmatrix}.$$

The first term in Eq.(14) corresponds to the successful discrimination, while the last term correspond to inconclusive result.

(5) To complete the nonlocal UD, Alice and Bob measure their systems and Alice sends one cbit to Bob according to her results. After a σ_z measurement is performed on ancilla A, we find either M_0 or M_1 has been generated remotely. M_0 acts to rotate remotely the nonorthogonal states $|\phi_\pm\rangle_B$ to $(|0\rangle_B + |1\rangle_B)$ or $(|0\rangle_B - |1\rangle_B)$, in which case we can distinguish with certainty (for any given $\varphi \in (0, \pi]$) between $|\phi_\pm\rangle_B$ by measuring σ_x of system B. If the ancilla is observed to be in the state $|1\rangle_A$, M_1 maps both states into inconclusive results, and the encoded information is completely lost.

Synthesizing all conditions, we obtain the probability of successful discrimination among different values of φ (i.e. among different settings of the ancilla and different pairs of the input states) as following:

$$P(\theta,\varphi) = \langle\phi_\pm|_B M_0^+ M_0|\phi_\pm\rangle_B = 2\sin^2\frac{\varphi}{2} \times \frac{\cos^2(\varphi/2)\sin^2(\theta/2)}{1 - \sin\varphi\cos(\theta/2)} = 2\sin^2(\varphi/2) f(\theta,\varphi). \quad (15)$$

This expression is obtained from condition (13) together with normalization relation $|a|^2 + |b|^2 = 1$. When $f(\theta,\varphi) = 1$, then $P = 2\sin^2(\varphi/2)$, which is identical to that in an ordinary local POVM. Ratio $f(\theta,\varphi)$ of the actual probability of successful discrimination to the optimal value of this probability is a function of controlled-rotation angle θ and angle φ between two considered state vectors (see Fig.1).

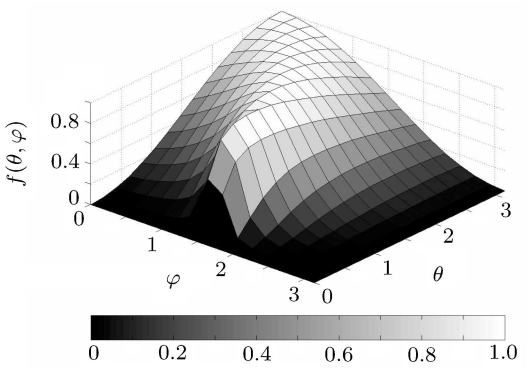


Fig.1. Ratio $f(\theta,\varphi)$ of the actual probability of successful discrimination to the optimal value of this probability as a function of controlled-rotation angle θ and angle φ between two considered state vectors.

We make a remark upon our result. If the value of parameter θ is somewhere between $\pi/6$ and π, the probability of success (as a function of φ) is very close to an optimal value in the relatively large range of φ. For example, the average value of $f(\theta_0,\varphi)$ over the interval of φ from 0 to $\pi/2$ is 0.916 when $\theta_0 = 0.7$rad (see Fig.2). We also plot some contours of $f(\theta,\varphi)$ in Fig.3. However, for $\varphi = \pi/2$ (orthogonal states) the probability of successful discrimination is lower than unity.

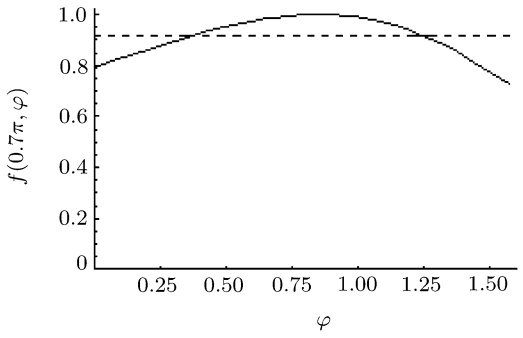


Fig.2. $f(\theta_0,\varphi)$ vs φ for $\theta_0 = 0.7$ rad. The dashed line shows that the average value of $f(\theta_0,\varphi)$ over the interval of φ from 0 to $\pi/2$ corresponds to $\theta_0 = 0.7$ rad and equals 0.916.

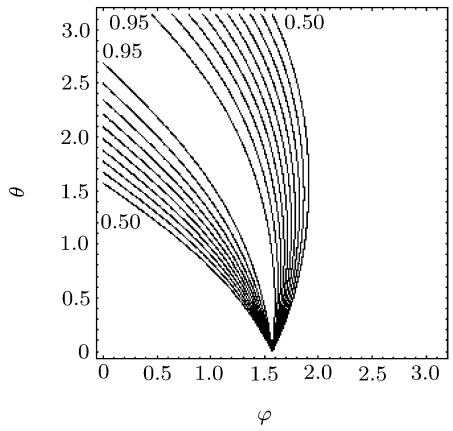


Fig.3. The contours of $f(\theta,\varphi)$ with the values of $f(\theta,\varphi)$ being 0.95, 0.90, 0.85, 0.80, 0.75, 0.70, .0.65, 0.60, 0.55 and 0.50 in sequence from inner to outer.

From the above it follows that it is possible to remotely discriminate probabilistically but unambiguously between two nonorthogonal states $|\phi_{\pm}\rangle_B = \cos(\varphi/2)|0\rangle_B \pm \sin(\varphi/2)|1\rangle_B$ for a large class of nonorthogonal pairs. The angle φ is encoded into a one-qubit ancillary state in a somewhat complicated way. The selection of the pair of states that should be unambiguously and nonlocally distinguished is made by the choice of the quantum state of ancillary qubit. This ancillary qubit state selects the measurement to be performed on the system, i. e. Alice has full control over the remote POVM and obtains the measurement result. This protocol has a good performance. It dose not achieve a maximum possible success probability for all input states, but for some subsets it can reach a value very close to an optimal value.

4. Conclusion

We have given a method to implement remotely the unambiguous quantum-state discrimination by using entanglements and LOCCs. Different from other local protocols, this protocol makes it possible for us to remotely and unambiguously discriminate between any two states that are symmetrically located around some fixed state [in the sense of Eq.(3)]. Bob's particular pair of states that can be remotely and unambiguously distinguished is specified by the state of an ancillary qubit that is held by Alice. The protocol consists of a remote POVM. Based on the theory of majorization, we explicitly construct the required remote POVM, which can be realized by performing a nonlocal controlled-rotation operation on Alice's ancilla A and Bob's qubit B, and the conventional local orthogonal measurement on ancilla. The implementation of the remote POVM in the protocol demands a small-scale quantum communication network, namely quantum circuit composed of universal quantum gates and quantum communication channels, to implement the corresponding nonlocal unitary operation. We have constructed the quantum network. Alice and Bob can use the constructed quantum network together with orthogonal measurement to implement the remote UD. The probability of successful discrimination is optimal only for one admissible pair. However, the protocol can be designed in such a way that the probability of successful discrimination is very close to an optimal value for a relatively large set of admissible pairs. In this approach Alice has full control over the remote POVM and obtains the measurement result. Recently, the nonlocal controlled-Not (CNOT) gate has been implemented experimentally in a linear optical setup and an experiment along this line, where a nonlocal rotation was implemented by using linear optics, has been reported in Ref.[34], so our protocol may be feasible in practice.

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