

Optimal dense coding with arbitrary pure entangled states

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We examine dense coding with an arbitrary pure entangled state sharing between the sender and the receiver. Upper bounds on the average success probability in approximate dense coding and on the probability of conclusive results in unambiguous dense coding are derived. We also construct the optimal protocol which saturates the upper bound in each case.

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I. INTRODUCTION

Dense coding [1] is a communication protocol which, making use of entanglement shared in prior between the sender (Alice) and the receiver (Bob), can improve the classical capacity of a noiseless quantum channel. In the original protocol proposed by Bennett and Wiesner in Ref.[1], with the assistance of a maximally entangled qubit pair, Alice can send faithfully 2 bits of classical information to Bob by sending a single qubit. Notice that it is only possible for Alice to send 1 bit of classical information by sending a qubit without the assistance of entanglement [2, 3]. The use of entanglement in this protocol doubles the classical capacity of the noiseless quantum channel. In the same paper, the authors generalized the protocol to transmit faithfully $2 \log_2 d$ bits of classical information, making use of a maximally entangled state in d -level quantum system.

The original dense coding protocol has been generalized by other authors in various directions, such as the case of continuous variables [4, 5] and multipartite communication [6–8]. Maximally entangled states are very difficult to prepare and store in practical applications, so it is important to consider the performance of dense coding when the states shared between the sender and the receiver are partially entangled. On the other hand, when only a partially entangled state is available, it is easy to check that perfect dense coding presented in Ref.[1] is impossible. That is, we can not hope to transmit faithfully $2 \log_2 d$ bits of classical information with certainty, provided that a partial entanglement in d -level quantum system is shared. To deal with the problem of dense coding with arbitrary pure entangled states, Hao et al. [9] initialized the exploration of probabilistic dense coding for qubit case, in which the protocol succeeds only with some probability less than 1. Probabilistic dense coding was further extended to higher dimensional case by Pati et al. [10] and Wu et al. [11]. Another clue of research,

discussed in Refs.[12] and [13], pays attention to investigation of the relation between the form and the amount of shared entanglement and the maximal size of alphabet which can be faithfully transmitted from Alice to Bob. Rather surprisingly, approximate dense coding in which there exists some probability of error has not considered in the literature.

In this paper, we consider dense coding with an arbitrary pure entangled state in both approximate case and unambiguous case. Our contribution is twofold: First, we derive an upper bound on the average success probability of dense coding in approximate case. An explicit protocol which saturates this bound is also given. Second, we consider the case of unambiguous dense coding and derive the optimal conclusive probability which turns out to be a constant for any input signal. We also construct explicitly a protocol in which this optimal probability is achieved.

II. STRATEGIES OF IMPERFECT DENSE CODING

This section devotes to the clarification of the differences between imperfect dense coding strategies presented in the literature and those proposed in this paper. To make the statements more rigorous, we first formulate the problem of dense coding as follows.

Suppose Alice and Bob share in prior an entangled pure state $|\Phi\rangle$ in Hilbert space $\mathcal{H}_d \otimes \mathcal{H}_d$ with the Schmidt decomposition

$$|\Phi\rangle = \sum_{i=0}^{d-1} \lambda_i |i\rangle |i\rangle \quad (1)$$

where $\lambda_0 \geq \dots \geq \lambda_{d-1} \geq 0$ and $\sum \lambda_i^2 = 1$. In addition, there exists a noiseless d -dimensional quantum channel by which Alice can send her particle faithfully to Bob. The purpose of dense coding is to transmit from Alice to Bob signals chosen from the set $\{0, 1, \dots, d^2 - 1\}$. The most general strategy is as follows. Alice encodes each possible signal $r \in \{0, 1, \dots, d^2 - 1\}$ into her particle by carrying out a general quantum operation \mathcal{E}_r on it, and then sends her particle to Bob through the noiseless

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quantum channel. After receiving Alice's particle, Bob performs a positive operator-valued measure (POVM for short) $\{\Pi_s\}$ on the joint system. The measurement result is used by Bob to make a guess on the signal Alice sent to him. Here we do not specify the range of subscript s in the POVM Bob performs, since as we will see in the following, it varies in different dense coding schemes.

As already indicated in the Introduction, when the state in Eq.(1) is partially entangled, i.e. $\lambda_0 < 1$, perfect dense coding which can faithfully transmit $2 \log_2 d$ bits of classical information with certainty is impossible. If a certain probability of error is permitted for Bob when guessing the signal Alice sent, the task of dense coding can, however, be achieved. This scheme is proposed in this paper and called approximate dense coding with its aim to maximize the success transmission probability

$$P_s = \sum_{r=0}^{d^2-1} p_r P(r|r). \quad (2)$$

Here p_r denotes the prior-probability of the occurrence of signal r , and $P(s|r)$ denotes the probability of Bob retrieving signal s when r was initially transmitted by Alice.

The probabilistic dense coding proposed in Refs.[9, 10] and the unambiguous one in Ref.[11], on the other hand, allow some probability with which the protocol fails with nothing transmitted from Alice to Bob. Once it succeeds, however, the signal Alice sent is recovered by Bob without error. That is, it is required that

$$P(s|r) = 0, \text{ for all } s \neq r. \quad (3)$$

The aim of this scheme is then maximize the conclusive probability

$$P_c = \sum_{r=0}^{d^2-1} p_r P(r|r) \quad (4)$$

under the constraint of Eq.(3).

In this paper, we adopt a different view of regarding unambiguous dense coding as a protocol which can faithfully transmit a random variable from the sender to the receiver. In other words, if the signals Alice encoded in her particle were drawn upon a probability distribution, after receiving Alice's particle, Bob should retrieve the distribution perfectly with some probability. As a consequence, by 'unambiguous' we mean that not only any signal is transmitted without error, but the post-probability of the signal occurring on Bob's side, conditioning that conclusive results are obtained, is the same as the prior-probability the signal was chosen on Alice's side. To be specific, not only Eq.(3) but also the following constraint

$$P(r|con) = p_r \quad (5)$$

is required, where $P(r|con)$ denotes the post-probability of the outcome r conditioning that conclusive results are obtained. The aim of unambiguous dense coding in our sense is then maximize the success probability in Eq.(4) under the constraints of Eqs.(3) and (5).

III. OPTIMAL DENSE CODING: APPROXIMATE CASE

In this section, we consider dense coding in approximate case. Suppose the operation \mathcal{E}_r Alice carries out on her particle to encode signal r is represented by Kraus operators as follows:

$$\mathcal{E}_r(\rho) = \sum_k E_{rk} \rho E_{rk}^\dagger, \quad (6)$$

and the POVM Bob performs on the joint system has the form $\{\Pi_r : r = 0, 1, \dots, d^2 - 1\}$. When the result r is obtained, Bob declares that the signal Alice sent is r . Suppose further that each Π_r has the decomposition

$$\Pi_r = \sum_t |\phi_{rt}\rangle\langle\phi_{rt}| \quad (7)$$

for some un-normalized states $|\phi_{rt}\rangle$. Here we omit the ranges of the subscripts k and t since they are unimportant for our discussion. Let the random variable X upon which Alice chooses the signals have the distribution $P(X = r) = p_r$. Then the success probability of transmitting X from Alice to Bob is

$$\begin{aligned} P_s &= \sum_{r=0}^{d^2-1} p_r P(r|r) \\ &= \sum_{r=0}^{d^2-1} p_r \text{Tr}(\Pi_r \sum_k (E_{rk} \otimes I) |\Phi\rangle\langle\Phi| (E_{rk}^\dagger \otimes I)). \end{aligned} \quad (8)$$

In what follows, we derive an upper bound on the average success probability

$$\mathbb{E}P_s = \int P_s d\mathbf{p} \quad (9)$$

of approximate dense coding over all possible random variables with range $\{0, 1, \dots, d^2 - 1\}$. Here the integral $\int d\mathbf{p}$ over the space of d^2 -dimensional probability distributions is performed using the uniform measure. Techniques used in the argument are mainly based on Ref.[14].

To begin with, we write the vectors $|\phi_{rt}\rangle$ under the Schmidt basis presented in Eq.(1) as

$$|\phi_{rt}\rangle = \sum_{i=0}^{d-1} |\phi_{rt}^i\rangle|i\rangle, \quad (10)$$

where again the vectors $|\phi_{rt}^i\rangle$ are not necessarily normalized. From the completeness of the POVM operators Π_i , we have

$$I_d \otimes I_d = \sum_r \Pi_r = \sum_{r,t} \sum_{i,j=0}^{d-1} |\phi_{rt}^i\rangle\langle\phi_{rt}^j| \otimes |i\rangle\langle j|, \quad (11)$$

and it follows that

$$\sum_{r,t} |\phi_{rt}^i\rangle\langle\phi_{rt}^j| = \delta_{ij} I_d \quad (12)$$

Taking Eqs.(1), (8), and (10) into Eq.(9), we have

$$\begin{aligned}\mathbb{E}P_s &= \sum_{r,k,t} \left(\int p_r d\mathbf{p} \right) |\langle \phi_{rt} | E_{rk} \otimes I | \Phi \rangle|^2 \\ &= \frac{1}{d^2} \sum_{r,k,t} \left| \sum_i \lambda_i \langle \phi_{rt}^i | E_{rk} | i \rangle \right|^2.\end{aligned}\quad (13)$$

The last equality holds because $\int p_r d\mathbf{p} = d^{-2}$ for any $r = 0, \dots, d^2 - 1$, which in turn is obvious from the symmetry and the identity $\int \sum_r p_r d\mathbf{p} = 1$.

We now recall the inequality

$$\sum_{\alpha=1}^N \left| \sum_{k=1}^M x_{k\alpha} \right|^2 \leq \left(\sum_{k=1}^M \sqrt{\sum_{\alpha=1}^N |x_{k\alpha}|^2} \right)^2 \quad (14)$$

from Ref.[14] which is simply the triangle inequality for M complex N -dimensional vectors $\mathbf{x}_k = (x_{k1}, \dots, x_{kN})$ with the standard quadratic norm $\|\mathbf{x}_k\|^2 = \sum_{\alpha=1}^N |x_{k\alpha}|^2$. So we proceed as

$$\mathbb{E}P_s \leq \frac{1}{d^2} \left(\sum_i \lambda_i \sqrt{\sum_{r,k,t} |\langle \phi_{rt}^i | E_{rk} | i \rangle|^2} \right)^2. \quad (15)$$

The term under the square root in the above expression can be further estimated by

$$\begin{aligned}&\sum_{r,k,t} |\langle \phi_{rt}^i | E_{rk} | i \rangle|^2 \\ &= \sum_{r,t} \langle \phi_{rt}^i | \phi_{rt}^i \rangle \sum_k \langle i | E_{rk}^\dagger \frac{|\phi_{rt}^i\rangle\langle\phi_{rt}^i|}{\langle\phi_{rt}^i|\phi_{rt}^i\rangle} E_{rk} | i \rangle \\ &\leq \sum_{r,t} \langle \phi_{rt}^i | \phi_{rt}^i \rangle \sum_k \langle i | E_{rk}^\dagger E_{rk} | i \rangle \\ &= \sum_{r,t} \langle \phi_{rt}^i | \phi_{rt}^i \rangle = d.\end{aligned}\quad (16)$$

The last equality is due to Eq.(12). Notice that we have implicitly assumed that $\langle \phi_{rt}^i | \phi_{rt}^i \rangle \neq 0$ for any r, t and i in the above argument. There is no loss of generality, however, since the above inequalities also hold when for some r, t and i , $\langle \phi_{rt}^i | \phi_{rt}^i \rangle = 0$. Thus finally we arrive at our desired bound on the average success probability in approximate dense coding which reads

$$\mathbb{E}P_s \leq \frac{1}{d} \left(\sum_{i=0}^{d-1} \lambda_i \right)^2. \quad (17)$$

In the following, we construct explicitly a protocol which saturates the bound presented in Eq.(17). This protocol is in fact the standard one for dense coding with higher dimensional maximally entangled states. To simplify the notations, we introduce two indexes m and n both taking values 0 through $d - 1$ to replace the single index r in the following argument. Let the operation \mathcal{E}_{mn}

performed by Alice corresponding to signal (m, n) be a generalized Pauli operation σ_{mn} such that

$$\sigma_{mn} = \sum_{k=0}^{d-1} e^{2\pi i k n / d} |k \oplus m\rangle\langle k| \quad (18)$$

where \oplus denotes addition modulo d . Let the POVM carried out by Bob be $\{\Pi_{mn} = |\phi_{mn}\rangle\langle\phi_{mn}|, m, n = 0, \dots, d - 1\}$ where

$$|\phi_{mn}\rangle = \frac{1}{\sqrt{d}} \sum_{k=0}^{d-1} e^{2\pi i k n / d} |k \oplus m\rangle |k\rangle. \quad (19)$$

It is direct to check that $\sum_{mn} \Pi_{mn} = I_d \otimes I_d$. Here in the above two equations, the basis $\{|k\rangle\}$ is the same as the basis $\{|i\rangle\}$ presented in Eq.(1). We now calculate the average success probability of this dense coding protocol as

$$\begin{aligned}\mathbb{E}P_s &= \frac{1}{d^2} \sum_{m,n=0}^{d-1} |\langle \phi_{mn} | \sigma_{mn} | \Phi \rangle|^2 \\ &= \frac{1}{d^3} \sum_{m,n=0}^{d-1} \left| \sum_{k,k'=0}^{d-1} \lambda_{k'} e^{2\pi i (k' - k)n / d} \langle k \oplus m | k' \oplus m \rangle \right|^2 \\ &= \frac{1}{d^3} \sum_{m,n=0}^{d-1} \left(\sum_{k=0}^{d-1} \lambda_k \right)^2 = \frac{1}{d} \left(\sum_{k=0}^{d-1} \lambda_k \right)^2.\end{aligned}\quad (20)$$

IV. OPTIMAL DENSE CODING : UNAMBIGUOUS CASE

We derive in the previous section the optimal strategy of approximate dense coding with an arbitrary pure entangled state. In this section, we consider the same problem in unambiguous dense coding. As pointed out in Section II, what we are concerned with in our notion of unambiguous dense coding is the transmission of random variables, so the specific signal as well as the probability the signal occurs must be recovered unambiguously on Bob's side. With this criteria, the general strategy for Alice and Bob is as follows. Alice carries out on her particle a quantum operation \mathcal{E}_r to encode the signal r , just as in approximate dense coding; while Bob's POVM must have an additional element indicating the inconclusive result. That is, the measurement should have the form $\{\Pi_?, \Pi_r; r = 0, 1, \dots, d^2 - 1\}$. When the result corresponding to $\Pi_?$ is obtained, the process fails, and nothing is transmitted from Alice to Bob.

Let $p_r = P(X = r)$ be the probability of Alice choosing the operation \mathcal{E}_r . Then the post-probability of the measurement outcome r conditioning that conclusive results are obtained is

$$P(r|con) = \frac{p_r P(con|r)}{\sum_r p_r P(con|r)} = \frac{p_r P(r|r)}{\sum_r p_r P(r|r)}. \quad (21)$$

The second equality holds because $P(s|r) = \delta_{rs}P(r|r)$ which in turn is due to the constraint that the dense coding scheme is error-free.

By definition, unambiguous dense coding protocols must transmit *any* random variable from Alice to Bob unambiguously, so it is required that $P(r|con) = p_r$ for any prior-probability distribution p_r . Thus we deduce $P(r|r) = C$, $r = 0, 1, \dots, d^2 - 1$, for a constant C independent of r . That is, to achieve unambiguous dense coding for any input random variable, the success probability must be the same for each signal Alice wishes to send. We further calculate the conclusive probability of the whole protocol as

$$P_c = \sum_r p_r P(con|r) = \sum_r p_r P(r|r) = C, \quad (22)$$

which is also independent of the distribution of the transmitted random variable X . It has been proven in Ref.[11] that in the case of constant conditional success probability, it holds $P_c \leq d\lambda_{d-1}^2$. So we finally have

$$\mathbb{E}P_c \leq d\lambda_{d-1}^2. \quad (23)$$

It is worth noting that since the conclusive probability P_c is independent of the prior distribution of X , the bound presented in Eq.(23) also applies if we take other quantities, e.g. the maximum success probability over all possible prior-probability distributions, as our criterions to judge the optimality of an unambiguous dense coding protocol.

Somewhat surprisingly, the bound presented in Eq.(23) for unambiguous dense coding coincides with the bound proposed in Ref.[15] for unambiguous teleportation. This can be regarded as a new evidence for the close connection between dense coding and teleportation.

To conclude this section, we construct an explicit protocol which saturates the bound in Eq.(23). Notice that this bound is just the maximal success probability of converting the partially entangled state in Eq.(1) into a maximally entangled state in the same Hilbert space using only local quantum operations and classical communication [16, 17]. A direct strategy for Alice and Bob is first converting the shared entanglement into a maximal one, and then utilizing this maximal entanglement to send information perfectly using the standard protocol.

This strategy is, however, not the optimal one in the sense that additional classical communication will be assumed in the process of entanglement conversion. Fortunately, we can construct as follows a direct protocol to saturate the bound without resorting to any additional resource. Let the operation \mathcal{E}_{mn} performed by Alice corresponding to the signal (m, n) be the general Pauli operation σ_{mn} defined in Eq.(18), just as in the optimal approximate protocol. The POVM carried out by Bob, however, has the following form

$$\Pi_{mn} = \frac{\lambda_{d-1}^2}{d} |\phi_{mn}\rangle\langle\phi_{mn}| \quad (24)$$

for $m, n = 0, \dots, d - 1$, and

$$\Pi_? = I_d \otimes I_d - \sum_{m,n=0}^{d-1} \Pi_{mn} \quad (25)$$

where the un-normalized state

$$|\phi_{mn}\rangle = \sum_{k=0}^{d-1} \lambda_k^{-1} e^{2\pi i kn/d} |k \oplus m\rangle |k\rangle. \quad (26)$$

Without loss of generality, we assume that $\lambda_{d-1} > 0$ (so $\lambda_k > 0$ for any $0 \leq k \leq d - 1$) because otherwise the bound is equal to 0, and it can be saturated trivially.

We now prove that the set of measurement operators in Eqs.(24) and (25) indeed constitute a POVM. This can be validated from the calculation

$$\begin{aligned} \sum_{m,n=0}^{d-1} \Pi_{mn} &= \lambda_{d-1}^2 \sum_{m,k} \lambda_k^{-2} |k \oplus m\rangle \langle k \oplus m| \otimes |k\rangle \langle k| \\ &= I_d \otimes \sum_k \left(\frac{\lambda_{d-1}}{\lambda_k} \right)^2 |k\rangle \langle k| \\ &\leq I_d \otimes I_d. \end{aligned} \quad (27)$$

Furthermore, for any signals (m, n) and (m', n') , we have

$$\begin{aligned} \text{Tr}(\Pi_{mn} \mathcal{E}_{m'n'}(|\Phi\rangle\langle\Phi|)) &= \frac{\lambda_{d-1}^2}{d} |\langle\phi_{mn}|\sigma_{m'n'}|\Phi\rangle|^2 \\ &= \frac{\lambda_{d-1}^2}{d} \left| \sum_{k,k'} \lambda_{k'} \lambda_k^{-1} e^{2\pi i (kn' - kn)/d} \langle k \oplus m | k \oplus m \rangle \langle k | k' \rangle \right|^2 \\ &= d\lambda_{d-1}^2 \delta_{mm'} \delta_{nn'}. \end{aligned} \quad (28)$$

The probability of conclusively transmitting the signal (m, n) is then $P[(m, n)|(m, n)] = d\lambda_{d-1}^2$, which is independent of the specific signal (m, n) and the prior-distribution. From these facts, it is easy to show that this protocol can indeed unambiguously transmit any random variable from Alice to Bob, and also, the bound presented in Eq.(23) for unambiguous dense coding is reached.

V. CONCLUSION

In this paper, we present optimal dense coding strategies for approximate and unambiguous cases when partial entanglement between the sender and the receiver is provided. These strategies are optimal in the sense that the average success probability (in approximate case) or the average probability of conclusive results (in unambiguous case) is maximized. Notice that the optimal average success probability for approximate dense coding given in Eq.(17) depends on the sum of all the Schmidt coefficients $\sum_{i=0}^{d-1} \lambda_i$, while in unambiguous dense coding, the optimal average conclusive probability presented

in Eq.(23) depends only on the least Schmidt coefficient λ_{d-1} . These results give new evidences to the correspondence between dense coding and teleportation since the same dependency can be found in approximate teleportation [14] and unambiguous teleportation [15].

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