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Efficient quantum error correction for fully correlated noise

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ABSTRACT

We investigate an efficient quantum error correction of a fully correlated noise. Suppose the noise is characterized by a quantum channel whose error operators take fully correlated forms given by $\sigma_x^{\otimes n}$, $\sigma_y^{\otimes n}$ and $\sigma_z^{\otimes n}$, where $n > 2$ is the number of qubits encoding the codeword. It is proved that (i) n qubits codeword encodes $(n - 1)$ data qubits when n is odd and (ii) n qubits codeword implements an error-free encoding, which encode $(n - 2)$ data qubits when n is even. Quantum circuits implementing these schemes are constructed.

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1. Introduction

In quantum information processing, information is stored and processed with a quantum system. A quantum system is always in contact with its surrounding environment, which leads to decoherence in the quantum system. Decoherence must be suppressed for quantum information stored in qubits to be intact. There are several proposals to fight against decoherence. Quantum error correction, abbreviated as QEC hereafter, is one of the most promising candidate to suppress environmental noise, which leads to decoherence [1]. By adding extra ancillary qubits, in analogy with classical error correction, it is possible to encode a data qubit to an n -qubit codeword in such a way that an error which acted in the error quantum channel is identified by measuring another set of ancillary qubits added for error syndrome readout. Then the correct codeword is recovered from a codeword suffering from a possible error by applying a recovery operation, whose explicit form is determined by the error syndrome readout.

In contrast with the conventional scheme outlined in the previous paragraph, there is a scheme in which neither syndrome

readouts nor syndrome readout ancilla qubits are required [2–5]. In particular, in [4,5], a general efficient scheme was proposed. A data qubit is encoded with encoding ancilla qubits by the same encoding circuit as the conventional one, after which a noisy channel is applied on the codeword. Subsequently, the inverse of the encoding circuit is applied on a codeword, which possibly suffers from an error. The resulting state is a tensor product of the data qubit state with a possible error and the ancilla qubit state. It is possible to correct erroneous data qubit state by applying correction gates with the ancilla qubits as control qubits and the data qubit as a target qubit.

This Letter presents two examples of error correcting codes falling in the second category. The noisy quantum channel is assumed to be fully correlated, which means all the qubits constituting the codeword are subject to the same error operators. In most physical realizations of a quantum computer, the system size is typically on the order of a few micrometers or less, while the environmental noise, such as electromagnetic wave, has a wavelength on the order of a few millimeters or centimeters. Then it is natural to assume all the qubits in the register suffer from the same error operator. To demonstrate the advantage of the second category, we restrict ourselves within the noise operators $X_n = \sigma_x^{\otimes n}$, $Y_n = \sigma_y^{\otimes n}$, $Z_n = \sigma_z^{\otimes n}$ in the following, where $n > 2$ is the number of constituent qubits in the codeword. We show that there exists an n -qubit encoding which accommodates an $(n - 1)$ -qubit data state if n is odd and an $(n - 2)$ -qubit data state if n is even. Although the channel is somewhat artificial as an error channel,

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we may apply our error correction scheme in the following situation. Suppose Alice wants to send qubits to Bob. Their qubit bases differ by unitary operations X_n, Y_n or Z_n . Even when they do not know which basis the other party employs, Alice can correctly send qubits by adding one extra qubit (when n is odd) or two extra qubits (when n is even).

Recently, the violation of the quantum Hamming bound due to code degeneracy was discussed in the case of arbitrarily correlated noise and the concept of the packing distance has been introduced [6]. In the present Letter, the packing distance is exactly derived for the fully correlated noise by using rank- k numerical range analysis. We state the theorems and prove them in the next section. The last section is devoted to summary and discussions.

2. Main theorems

In the following, σ_i denotes the i th component of the Pauli matrices and we take the basis vectors

$$|0\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \text{and} \quad |1\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

so that σ_z is diagonalized. We introduce operators X_n, Y_n and Z_n acting on the n -qubit space $\mathbb{C}^{2^n} = \otimes_{i=1}^n \mathbb{C}^2$, where $n > 2$ as mentioned before.

Let A_1, A_2, A_3 be $m \times m$ complex matrices, and let $k \in \{1, \dots, m-1\}$. Denote by $\Lambda_k(A_1, A_2, A_3)$ the (joint) rank- k numerical range of (A_1, A_2, A_3) , which is the collection of $(a_1, a_2, a_3) \in \mathbb{C}^3$ such that $PA_jP = a_jP$ for some $m \times m$ rank- k orthogonal projection P [7–9]. A quantum channel of the form

$$\Phi(\rho) = p_0\rho + p_1X_n\rho X_n^\dagger + p_2Y_n\rho Y_n^\dagger + p_3Z_n\rho Z_n^\dagger$$

with $p_0, p_1, p_2, p_3 > 0, \sum_{i=0}^3 p_i = 1,$ (1)

has a k -dimensional quantum error correcting code (QECC) if and only if $\Lambda_k(X_n, Y_n, Z_n) \neq \emptyset$. To prove this statement, we need to recall the Knill–Laflamme correctability condition, which asserts that given a quantum channel $\Phi: M_n \rightarrow M_n$ with error operators $\{F_i\}_{1 \leq i \leq r}$, \mathcal{V} is a QECC of Φ if and only if $PF_i^\dagger F_jP = \mu_{ij}P$, where $P \in M_n$ is the projection operator with the range space \mathcal{V} [10]. It should be clear that $\Lambda_k(\{F_i^\dagger F_j\}_{1 \leq i, j \leq r}) \neq \emptyset$ if and only if there is a QECC with dimension k . Now it follows from $X_n^2 = Y_n^2 = Z_n^2 = I$ and the relations

$$X_n Y_n = i^n Z_n, \quad Y_n Z_n = i^n X_n, \quad Z_n X_n = i^n Y_n$$

that the channel (1) has a k -dimensional QECC if and only if

$$\Lambda_k(X_n, Y_n, Z_n, I) \neq \emptyset.$$

By noting that $PIP = 1 \cdot P$ irrespective of rank P , we find $\Lambda_k(X_n, Y_n, Z_n) \neq \emptyset$ if and only if $\Lambda_k(X_n, Y_n, Z_n, I) \neq \emptyset$.

Theorem 2.1. *Suppose $n > 2$ is odd. Then $\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) \neq \emptyset$.*

Proof. Our proof is constructive. For $j_1, \dots, j_n \in \{0, 1\}$, denote $|j_1, \dots, j_n\rangle = \otimes_{i=1}^n |j_i\rangle$. Let

$$\mathcal{V} = \text{Span}\{|j_1, \dots, j_n\rangle: \text{the number of } i \text{ with } j_i = 1 \text{ is even}\}.$$

Then $\dim \mathcal{V} = \sum_{r \text{ is even}} \binom{n}{r} = \frac{1}{2}((1+1)^n + (1-1)^n) = 2^{n-1}$, where $\binom{n}{r}$ is the number of r -combinations from n elements. Since

$$\begin{aligned} \sigma_x|0\rangle &= |1\rangle, & \sigma_x|1\rangle &= |0\rangle, & \sigma_y|0\rangle &= i|1\rangle, \\ \sigma_y|1\rangle &= -i|0\rangle, & \sigma_z|0\rangle &= |0\rangle, & \sigma_z|1\rangle &= -|1\rangle, \end{aligned}$$

we have

$$X_n|v\rangle, Y_n|v\rangle \in \mathcal{V}^\perp \quad \text{and} \quad Z_n|v\rangle = |v\rangle \quad \text{for all } |v\rangle \in \mathcal{V}.$$

Let P be the orthogonal projection onto \mathcal{V} . Then the above observation shows that $PX_nP = PY_nP = 0$ and $PZ_nP = P$. Therefore, $(0, 0, 1) \in \Lambda_{2^{n-1}}(X_n, Y_n, Z_n)$, which shows that $\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) \neq \emptyset$ and hence \mathcal{V} is shown to be a 2^{n-1} -dimensional QECC. \square

Now let us turn to the even n case. We first state a lemma which is necessary to prove the theorem.

Lemma 2.2. *Let $A \in M_N$ be a normal matrix. Then the rank- k numerical range of A is the intersection of the convex hulls of any $N - k + 1$ eigenvalues of A .*

The proof of the lemma is found in [9].

Theorem 2.3. *Suppose $n > 2$ is even. Then $\Lambda_{2^{n-2}}(X_n, Y_n, Z_n) \neq \emptyset$ but $\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) = \emptyset$.*

Proof. Let $n = 2m$. By Theorem 2.1, $\Lambda_{2^{n-2}}(X_{n-1}, Y_{n-1}, Z_{n-1}) \neq \emptyset$. Consider

$$\mathcal{V}' = \text{Span}\{|0\rangle|j_1, \dots, j_{n-1}\rangle: \text{the number of } i \text{ with } j_i = 1 \text{ is even}\}.$$

Observe that the projection P onto \mathcal{V}' satisfies $PX_nP = PY_nP = 0$ and $PZ_nP = P$ and hence $(0, 0, 1) \in \Lambda_{2^{n-2}}(X_n, Y_n, Z_n)$, which proves $\Lambda_{2^{n-2}}(X_n, Y_n, Z_n) \neq \emptyset$.

Since $\{X_n, Y_n, Z_n\}$ is a commuting family, X_n, Y_n and Z_n can be diagonalized simultaneously. We may assume that

$$\begin{aligned} X_n &= I_{2^{n-1}} \oplus (-I_{2^{n-1}}) \quad \text{and} \\ Y_n &= I_{2^{n-2}} \oplus (-I_{2^{n-2}}) \oplus I_{2^{n-2}} \oplus (-I_{2^{n-2}}). \end{aligned} \tag{2}$$

Since $\sigma_x\sigma_y = i\sigma_z$, we have

$$\begin{aligned} Z_n &= (-1)^m X_n Y_n \\ &= (-1)^m (I_{2^{n-2}} \oplus (-I_{2^{n-2}}) \oplus (-I_{2^{n-2}}) \oplus I_{2^{n-2}}). \end{aligned} \tag{3}$$

Let us show that $\Lambda_{2^{n-1}}(X_n, Y_n) = \{(0, 0)\}$. We first note the identity $\Lambda_k(H, K) = \Lambda_k(H + iK)$ for Hermitian H, K . Let us replace H by X_n and K by Y_n to obtain $\Lambda_k(X_n, Y_n) = \Lambda_k(X_n + iY_n)$. Since X_n and Y_n commute, $X_n + iY_n$ is normal and Lemma 2.2 is applicable. From Eqs. (2) and (3), we find $X_n + iY_n$ has eigenvalues $1 + i, 1 - i, -1 + i, -1 - i$ and each eigenvalue is 2^{n-2} -fold degenerate. By taking $N = 2^n$ and $k = 2^{n-1}$ in Lemma 2.2, we find the rank- 2^{n-1} numerical range of $X_n + iY_n$ is the intersection of the convex hulls of any $2^n - 2^{n-1} + 1 = 2^{n-1} + 1$ eigenvalues. Since each eigenvalue has multiplicity 2^{n-2} , each convex hull involves at least three eigenvalues. By inspecting four eigenvalues plotted in the complex plane, we easily find the intersection of all the convex hulls is a single point $(0, 0)$, which proves $\Lambda_{2^{n-1}}(X_n, Y_n) = \{(0, 0)\}$. Similarly, we prove $\Lambda_{2^{n-1}}(Y_n, Z_n) = \{(0, 0)\}$. From these equalities we obtain

$$\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) \subseteq \{(0, 0, 0)\}.$$

Suppose $\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) \neq \emptyset$. Let P be a rank- 2^{n-1} projection such that $PX_nP = PY_nP = PZ_nP = 0$. Let

$$P = \begin{bmatrix} P_{11} & P_{12} \\ P_{12}^\dagger & P_{22} \end{bmatrix}$$

where each P_{ij} has size $2^{n-1} \times 2^{n-1}$. From $P^2 = P$ and $PX_nP = 0$, we have four independent equations

$$P_{11}^2 + P_{12}P_{12}^\dagger = P_{11}, \quad P_{11}^2 - P_{12}P_{12}^\dagger = 0,$$

$$P_{22}^2 + P_{12}^\dagger P_{12} = P_{22}, \quad P_{22}^2 - P_{12}^\dagger P_{12} = 0.$$

Let $P_{12} = UDV^\dagger$ be the singular value decomposition of P_{12} , where D is a nonnegative diagonal matrix and $U, V \in U(2^{n-1})$. Then the above equations are solved as

$$P_{11} = UDU^\dagger, \quad P_{22} = VDV^\dagger, \quad 2D^2 = D.$$

By collecting these results, we find that the projection operator is decomposed as

$$P = \begin{bmatrix} U & 0 \\ 0 & V \end{bmatrix} \begin{bmatrix} D & D \\ D & D \end{bmatrix} \begin{bmatrix} U^\dagger & 0 \\ 0 & V^\dagger \end{bmatrix}.$$

Since $\text{rank } P = 2^{n-1}$ and $P^2 = P$, it follows from $2D^2 = D$ that $D = \frac{1}{2}I_{2^{n-1}}$. Let

$$A = U^\dagger(I_{2^{n-2}} \oplus (-I_{2^{n-2}}))U \quad \text{and} \quad B = V^\dagger(I_{2^{n-2}} \oplus (-I_{2^{n-2}}))V.$$

Then both A and B are non-singular. On the other hand, the assumption $PY_nP = PZ_nP = 0$ implies $A + B = A - B = 0$ and hence $A = B = 0$, which is a contradiction. Therefore, $\Lambda_{2^{n-1}}(X_n, Y_n, Z_n) = \emptyset$. \square

In the following, we give an explicit construction of QECC for Φ in Eq. (1) with odd n . The technique is based on Theorem 2.1 and the results in [5]. Let W be a $2^n \times 2^{n-1}$ matrix with columns in the set

$$\{|j_1, \dots, j_n\rangle: \text{the number of } i \text{ where } j_i = 1 \text{ is even}\}. \quad (4)$$

Define the $2^n \times 2^n$ matrix $R = [W \ X_nW]$. In our QEC, an $(n-1)$ -qubit state ρ is encoded with one ancilla qubit $|0\rangle$ as $R(|0\rangle\langle 0| \otimes \rho)R^\dagger$. Then a noisy quantum channel Φ is applied on the encoded state and subsequently the recovery operation R^\dagger is applied so that the decoded state automatically appears in the output with no syndrome measurements. Our QEC is concisely summarized as

$$R^\dagger \Phi(R(|0\rangle\langle 0| \otimes \rho)R^\dagger)R = \rho_a \otimes \rho \quad \text{for all } \rho \in M_{2^{n-1}}, \quad (5)$$

where $\rho_a = (p_0 + p_3)|0\rangle\langle 0| + (p_1 + p_2)|1\rangle\langle 1|$.

Choosing an encoding matrix amounts to assigning the last 2^{n-1} columns of R so that of R is unitary. Therefore there are large degrees of freedom in the choice of encoding. In the following examples, we have chosen encoding whose quantum circuit can be implemented with the least number of CNOT gates. Since our decoding circuit is the inverse of the encoding circuit, it is also implemented with the least number of CNOT gates.

When $n = 3$, the unitary operation R can be chosen as

$$R = |000\rangle\langle 000| + |011\rangle\langle 001| + |110\rangle\langle 010| + |101\rangle\langle 011| \\ + |111\rangle\langle 100| + |100\rangle\langle 101| + |001\rangle\langle 110| + |010\rangle\langle 111|.$$

When $n = 5$, R can be chosen as

$$R = |00000\rangle\langle 00000| + |00011\rangle\langle 00001| + |00110\rangle\langle 00010| \\ + |00101\rangle\langle 00011| + |01100\rangle\langle 00100| + |01111\rangle\langle 00101| \\ + |01010\rangle\langle 00110| + |01001\rangle\langle 00111| + |11000\rangle\langle 01000| \\ + |11011\rangle\langle 01001| + |11110\rangle\langle 01010| + |11101\rangle\langle 01011| \\ + |10100\rangle\langle 01100| + |10111\rangle\langle 01101| + |10010\rangle\langle 01110| \\ + |10001\rangle\langle 01111| + |11111\rangle\langle 10000| + |11100\rangle\langle 10001| \\ + |11001\rangle\langle 10010| + |11010\rangle\langle 10011| + |10011\rangle\langle 10100|$$

$$+ |10000\rangle\langle 10101| + |10101\rangle\langle 10110| + |10110\rangle\langle 10111| \\ + |00111\rangle\langle 11000| + |00100\rangle\langle 11001| + |00001\rangle\langle 11010| \\ + |00010\rangle\langle 11011| + |01011\rangle\langle 11100| + |01000\rangle\langle 11101| \\ + |01101\rangle\langle 11110| + |01110\rangle\langle 11111|.$$

Fig. 1 shows quantum circuits of the matrix R for $n = 3$ and $n = 5$. It follows from Eq. (5) that the recovery circuit is the inverse of the encoding circuit. It seems, at first sight, that the implementations given in Fig. 1 contradict with Eq. (5) since the controlled NOT gate in the end of the recovery circuit is missing in the encoding circuit. Note, however, that the top qubit is set to $|0\rangle$ initially and the controlled NOT gate is safely omitted without affecting encoding.

We construct a decoherence-free encoding when n is even as follows. The codeword in this case is immune to the noise operators, which is an analogue of noiseless subspace/subsystem introduced in [11,12]. Let $|e\rangle$ be an arbitrary element in a similar set as Eq. (4) defined for even n . Then evidently a vector

$$\frac{1}{\sqrt{2}}(|e\rangle + X_n|e\rangle)$$

is separately invariant under the action of X_n , Y_n and Z_n . There are

$$\frac{1}{2} \sum_{r=\text{even}} \binom{n}{r} = 2^{n-2}$$

orthogonal vectors of such form, e.g. we have four vectors,

$$\frac{1}{\sqrt{2}}(|0000\rangle + |1111\rangle), \quad \frac{1}{\sqrt{2}}(|0011\rangle + |1100\rangle), \\ \frac{1}{\sqrt{2}}(|0101\rangle + |1010\rangle), \quad \frac{1}{\sqrt{2}}(|0110\rangle + |1001\rangle), \quad (6)$$

for $n = 4$. Thus we find a decoherence-free encoding for $n - 2 = 2$ qubits by projecting onto this invariant subspace spanned by these basis vectors. It should be noted that the projection operator P to the subspace spanned by the four vectors in Eq. (6) satisfies $\text{rank } P = 4$ and $PX_4P = PY_4P = PZ_4P = P$, which shows $(1, 1, 1) \in \Lambda_4(X_4, Y_4, Z_4)$. It is easy to generalize this result to cases with arbitrary $n = 2m > 2$. Figs. 2(a) and 2(b) depict quantum circuits for (a) $n = 4$ and (b) $n = 6$, respectively.

3. Summary and discussions

We have shown that there is a quantum error correction which suppresses fully correlated errors of the form $\{\sigma_x^{\otimes n}, \sigma_y^{\otimes n}, \sigma_z^{\otimes n}\}$, in which n qubits are required to encode (i) $n - 1$ data qubit states when n is odd and (ii) $n - 2$ data qubit states when n is even. We have proved these statements by using operator theoretical technique. Neither syndrome measurements nor ancilla qubits for syndrome measurement are required in our scheme, which makes physical implementation of our scheme highly practical. Examples with $n = 3$ and $n = 5$ are analyzed in detail and explicit quantum circuits implementing our QEC with the least number of CNOT gate were obtained.

Since the error operators are closed under matrix multiplication, errors can be corrected even when they act on the codeword many times.

A somewhat similar QEC has been reported in [6]. They analyzed a partially correlated noise, where the error operators acts on a fixed number of the codeword qubits simultaneously. They have shown that the quantum packing bound was violated by taking advantage of degeneracy of the codes. Justification of such a noise physically, however, seems to be rather difficult. They have also

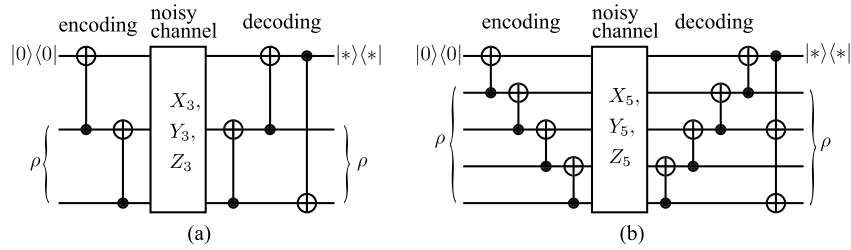


Fig. 1. Encoding and recovery circuits, which encode and recover an arbitrary $(n - 1)$ -qubit state ρ with a single ancilla qubit initially in the state $|0\rangle\langle 0|$. The circuit (a) is for $n = 3$ while (b) is for $n = 5$. The quantum channel in the box represents a quantum operation with fully correlated noise given in Eq. (1). The output ancilla state is $* = 0$ (1) for error operators $I^{\otimes 3}$ and Z_3 (X_3 and Y_3) for $n = 3$ and $* = 0$ (1) for $I^{\otimes 5}$ and Z_5 (X_5 and Y_5) for $n = 5$.

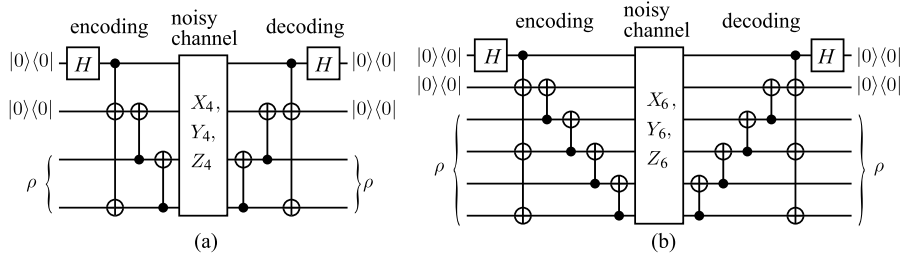


Fig. 2. Encoding and recovery circuits, which encode and recover an arbitrary $(n - 2)$ -qubit state ρ with two ancilla qubit initially in the state $|00\rangle\langle 00|$. The circuit (a) is for $n = 4$ while (b) is for $n = 6$. The quantum operation in the box represents a quantum operation with fully correlated noise given in Eq. (1). The output ancilla state is always $|00\rangle\langle 00|$, irrespective of error operators acted in the channel.

shown that correlated noise acting on an arbitrary number n of qubits can encode $k = n - 2$ data qubits. In contrast, we have analyzed a fully correlated noise, which shows the highest degeneracy, and have shown that $k = n - 1$ data qubits can be encoded with an n -qubit codeword when n is odd. Clearly, our QEC suppressing fully correlated errors is optimal as it is clear that one cannot encode n qubits as data qubits for odd n and we have shown that one cannot encode $n - 1$ qubits for even n .

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