Analog quantum error correction with encoding a qubit into an oscillator

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I Toward a large-scale quantum computation
   Continuous variable QC
   GKP qubit
   Our work

II Analog quantum error correction
   Proposal - likelihood function -
   Error model in our work
   Three qubit bit flip code
   C4/C6 code
   Surface code
   Summary
Outline

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## Toward large-scale quantum computation

Large-scale QC requires large-scale entangled states

<table>
<thead>
<tr>
<th>Technique</th>
<th>Number of qubits entangled</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapped ions</td>
<td>14</td>
</tr>
<tr>
<td>Superconducting</td>
<td>10</td>
</tr>
</tbody>
</table>

*References*

3. J. Yoshikawa et al., APL Photonics **1**, 060801 (2016)
Toward large-scale quantum computation

- Large-scale QC requires large-scale entangled states
  - Trapped ions: 14 qubits entangled \[1\]
  - Superconducting: 10 qubits entangled \[2\]
  - Squeezed vacuum state in optical field: \(1,000,000\) qumodes entangled \[3\]

**Vacuum state**

\[
\begin{array}{c}
p \\
\downarrow \quad q
\end{array}
\quad \overset{squeezing}{\rightarrow} \quad \begin{array}{c}
p \\
\downarrow \quad q
\end{array}
\]

**Squeezed vacuum state**

Increase of the squeezing level improves measurement accuracy in \(q\) quadrature

\(q(p):\) real (imaginary) part of optical field amplitude

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\[2\] C. Song et al., arXiv:1703.10302 (2017)
\[3\] J. Yoshikawa et al., APLPhotonics **1**, 060801 (2016)
Continuous variable quantum computation

- Large-scale QC with only squeezed vacuum (SV) states is impossible because of accumulation of errors [4]
- Continuous variable (CV) state needs to be digitized using an appropriate code, such as the GKP qubit

Large-scale QC with only squeezed vacuum (SV) states is **impossible** because of accumulation of errors \[4\]

Continuous variable (CV) state needs to be digitized using an appropriate code, such as the GKP qubit

**GKP qubit** \[5\]

\[
\begin{align*}
|0\rangle & \propto \sum_{t=-\infty}^{\infty} \int e^{-2\pi \delta^2 t^2} e^{-\left(q-2t\sqrt{\pi}\right)^2/(2\delta^2)} |q\rangle dq \\
|1\rangle & \propto \sum_{t=-\infty}^{\infty} \int e^{\pi \delta^2 (2t+1)^2/2} e^{-\left(q-(2t+1)\sqrt{\pi}\right)^2/(2\delta^2)} |q\rangle dq
\end{align*}
\]

$\delta^2$: variance of the GKP qubit

Gottesman-Kitaev-Preskill (GKP) qubit

Probability distribution

| $0\rangle$ state

| $1\rangle$ state

$q$

$-4\sqrt{\pi}$ $-2\sqrt{\pi}$ $0$ $2\sqrt{\pi}$ $4\sqrt{\pi}$

$-3\sqrt{\pi}$ $-\sqrt{\pi}$ $0$ $\sqrt{\pi}$ $3\sqrt{\pi}$
Gottesman-Kitaev-Preskill (GKP) qubit

Probability distribution

| 0 state
| 0 state

| 1 state
| 1 state

Area where state is identified as 0 state
Area where state is identified as 1 state
Gottesman-Kitaev-Preskill (GKP) qubit

Probability distribution

| 0⟩ state

Area where state is identified as 0 state

| 1⟩ state

Area where state is identified as 1 state

Measurement error

The more the squeezing level decreases, the larger measurement error probability becomes

Decrease in squeezing level

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Toward large-scale QC with the GKP qubit

Advantage

- Large-scale QC with the GKP qubits is possible
- GKP qubits can be entangled in the same way as SV states

Implementation

- Several methods to generate the GKP qubit are proposed [6,7]
- Achievable squeezing level of SV state is 15 dB [8]
Toward large-scale QC with the GKP qubit

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Implementation

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- Achievable squeezing level of SV state is 15 dB [8]

Problem

- Difficulty to experimentally generate the GKP qubit with the squeezing level 14.8 dB required for large-scale QC [4]

Proposal

- To reduce the required squeezing level, we have focused on analog information contained in the GKP qubit
- We propose a maximum-likelihood method which harnesses the analog information and improves QEC performance

Main results [9]

- The first proposal to achieve the hashing bound for the quantum capacity of the Gaussian quantum channel
- The required squeezing level can be reduced by \( \sim 1 \text{ dB} \)
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The true deviation $\Delta$ obeys the Gaussian distribution $f(x)$.
We regard the Gaussian distribution as a **likelihood function** $f(|\Delta|)$.
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We regard the Gaussian distribution as a likelihood function $f(|\Delta|)$.

Ex.) When we obtain the measurement outcome $q_m$, we consider two possibilities to determine the bit value 0 or 1.

- Area where state is identified as 0 state
- Area where state is identified as 1 state

$q_m$: Measurement outcome
The true deviation $\bar{\Delta}$ obeys the Gaussian distribution $f(x)$.
We regard the Gaussian distribution as a likelihood function $f(|\bar{\Delta}|)$.

Ex.) When we obtain the measurement outcome $q_m$, we consider two possibilities to determine the bit value 0 or 1.

$\Delta_m$: Measurement deviation  
$q_m$: Measurement outcome  

Area where state is identified as 0 state  
Area where state is identified as 1 state
The true bit value is 0

Ex.) When we obtain the measurement outcome \( q_m \),
we consider two possibilities to determine the bit value 0 or 1.

The true deviation \( \bar{\Delta} \) obeys the Gaussian distribution \( f(x) \).
We regard the Gaussian distribution as a likelihood function \( f(|\bar{\Delta}|) \).

\( q_m \): Measurement outcome
\( \Delta_m \): Measurement deviation

Area where state is identified as 0 state  Area where state is identified as 1 state
The true deviation $\overline{\Delta}$ obeys the Gaussian distribution $f(x)$. We regard the Gaussian distribution as a likelihood function $f(|\overline{\Delta}|)$.

Ex.) When we obtain the measurement outcome $q_m$, we consider two possibilities to determine the bit value 0 or 1.

The true bit value is 0.

$\Delta_m$; Measurement deviation

$\Delta_m$; Measurement deviation

$|\Delta| = \Delta_m$

$q_m$: Measurement outcome

$\Delta_m$: Measurement deviation

$\overline{\Delta}$: True deviation
The true bit value is 0

\[ \Delta_m \]

\[ q_m \]

true deviation \( |\bar{\Delta}| = \Delta_m \)

Ex.) When we obtain the measurement outcome \( q_m \), we consider two possibilities to determine the bit value 0 or 1

The true bit value is 1

\[ q_m \]

Area where state is identified as 0 state

Area where state is identified as 1 state

\( q_m \): Measurement outcome  \( \Delta_m \): Measurement deviation \( \bar{\Delta} \): True deviation
The true deviation $\bar{\Delta}$ obeys the Gaussian distribution $f(x)$
We regard the Gaussian distribution as a likelihood function $f(|\bar{\Delta}|)$

Ex.) When we obtain the measurement outcome $q_m$, we consider two possibilities to determine the bit value 0 or 1.

The true bit value is 0

The true bit value is 1

$q_m$: Measurement outcome  $\Delta_m$: Measurement deviation  $\bar{\Delta}$: True deviation
Error model in this work

The Gaussian quantum channel

The Gaussian quantum channel (GQC) leads to a displacement in the quadrature by a complex Gaussian random variable [5]

Described by superoperator $\zeta$ acting on density operator $\rho$ as

$$\rho \rightarrow \zeta(\rho) = \frac{1}{\pi \xi^2} \int d^2 \alpha e^{-|\alpha|^2/\xi^2} D(\alpha) \rho D(\alpha)^\dagger$$

$D(\alpha)$ is a displacement operator in the phase space.

The GQC conserves the position of the Gaussian peak, but increases the variance by $\xi^2$
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Single logical qubit is encoded into three qubits

\[
\alpha |0\rangle + \beta |1\rangle \rightarrow \alpha |000\rangle_{123} + \beta |111\rangle_{123} \quad (|\alpha|^2 + |\beta|^2 = 1)
\]
Ex.) Three-qubit bit-flip code

Single logical qubit is encoded into three qubits

\[ \alpha |0\rangle + \beta |1\rangle \rightarrow \alpha |000\rangle_{123} + \beta |111\rangle_{123} \quad (|\alpha|^2 + |\beta|^2 = 1) \]

- **Bit flip error**
  - No error: \[ \alpha |000\rangle_{123} + \beta |111\rangle_{123} \]
  - On qubit 1: \[ \alpha |100\rangle_{123} + \beta |011\rangle_{123} \]
  - On qubit 2&3: \[ \alpha |011\rangle_{123} + \beta |100\rangle_{123} \]
  - On qubit 2: \[ \alpha |010\rangle_{123} + \beta |101\rangle_{123} \]
  - On qubit 1&3: \[ \alpha |101\rangle_{123} + \beta |010\rangle_{123} \]
  - \ldots

- **Error pattern**
  - \[ \alpha |000\rangle_{123} + \beta |111\rangle_{123} \]
  - \[ \alpha |100\rangle_{123} + \beta |011\rangle_{123} \]
  - \[ \alpha |011\rangle_{123} + \beta |100\rangle_{123} \]
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Single logical qubit is encoded into three qubits

\[ \alpha |0\rangle + \beta |1\rangle \rightarrow \alpha |000\rangle_{123} + \beta |111\rangle_{123} \quad (|\alpha|^2 + |\beta|^2 = 1) \]

- **Bit flip error**
  - No error
  - on qubit 1
  - on qubit 2&3

- **Error pattern**
  - \( \alpha |000\rangle_{123} + \beta |111\rangle_{123} \)
  - \( \alpha |100\rangle_{123} + \beta |011\rangle_{123} \)
  - \( \alpha |011\rangle_{123} + \beta |100\rangle_{123} \)

The patterns of error on qubit 1 and 2&3 have same syndrome

In conventional method based on majoritv voting, the pattern of error on qubit 1 is selected.
Analog QEC for three-qubit bit-flip code

A quantum circuit for three-qubit bit-flip code

After GQC

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After GQC, the true deviations of qubit 1, 2, 3 become $\overline{\Delta}_1$, $\overline{\Delta}_2$, and $\overline{\Delta}_3$, respectively.

**Ideal GKP qubit**
Analog QEC for three-qubit bit-flip code

A quantum circuit for three-qubit bit-flip code

After GQC, the true deviations of qubit 1, 2, 3 become $\bar{\Delta}_1$, $\bar{\Delta}_2$, and $\bar{\Delta}_3$, respectively.

Encoding

(data qubit) qubit 1 $|\tilde{\psi}\rangle_1$
qubit 2 $|\tilde{0}\rangle_2$
qubit 3 $|\tilde{0}\rangle_3$

GQC

$\bar{\Delta}_1$
$\bar{\Delta}_2$
$\bar{\Delta}_3$

Error correction

After CNOT, the true deviation of ancilla 1 is $\bar{\Delta}_1 + \bar{\Delta}_2$, ancilla 2 is $\bar{\Delta}_2 + \bar{\Delta}_3$, and ancilla 3 is $\bar{\Delta}_3$, assuming ancilla qubits are ideal.

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Analog QEC for three-qubit bit-flip code

A quantum circuit for three-qubit bit-flip code

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Ideal GKP qubit

After CNOT, the true deviation of ancilla 1 is $\bar{\Delta}_1 + \bar{\Delta}_2$, ancilla 2 is $\bar{\Delta}_2 + \bar{\Delta}_3$, and ancilla 3 is $\bar{\Delta}_3$, assuming ancilla qubits are ideal.

From the measurement of ancillae, we obtain the measurement deviations $\Delta_{mi}$ ($i=1,2,3$)

**Ex.) No error**
we obtain the $\bar{\Delta}_i$ ($i=1,2,3$) correctly

**Ex.) Double errors on qubit 2 and 3**
we need to decide between single error on qubit 1 and double errors on qubit 2&3
Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1, \Delta m_2,$ and $\Delta m_3$, there are the two possibilities as follows:
Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1$, $\Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:
Syndrome with analog information

Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1$, $\Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:

Error on qubit 1

Error on qubit 1

$q^{m_1}$

$q^{m_2}$

$q^{m_3}$

$q^{m_1}$

$q^{m_2}$

$q^{m_3}$

$q^{m_1}$

$q^{m_2}$

$q^{m_3}$

$q^{m_1}$

$q^{m_2}$

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Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1$, $\Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:

**Error on qubit 1**

Likelihood for error on qubit 1:

$$f(\sqrt{\pi} - \Delta m_1) \times f(\Delta m_2) \times f(\Delta m_3)$$
 Syndrome with analog information

Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1$, $\Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:

**Error on qubit 1**

Likelihood for error on qubit 1

$$f(\sqrt{\pi} - \Delta m_1) \times f(\Delta m_2) \times f(\Delta m_3)$$

**Errors on qubit 2 & 3**

Likelihood for errors on qubit 2 & 3

$$f(\Delta m_1) \times f(\sqrt{\pi} - \Delta m_2) \times f(\sqrt{\pi} - \Delta m_3)$$
Syndrome with analog information

Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1$, $\Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:

Error on qubit 1

Likelihood for error on qubit 1

$f(\sqrt{\pi} - \Delta m_1) \times f(\Delta m_2) \times f(\Delta m_3)$

Errors on qubit 2 & 3

Likelihood for errors on qubit 2 & 3

$f(\Delta m_1) \times f(\sqrt{\pi} - \Delta m_2) \times f(\sqrt{\pi} - \Delta m_3)$

The likelihoods for qubit 2&3 are almost the same
Syndrome with analog information

Ex.) If double errors on qubit 2 and 3, and we obtain the measurement deviation of three qubits $\Delta m_1, \Delta m_2$, and $\Delta m_3$, there are the two possibilities as follows:

Error on qubit 1

Likelihood for error on qubit 1

$$f(\sqrt{\pi} - \Delta m_1) \times f(\Delta m_2) \times f(\Delta m_3)$$

Errors on qubit 2 & 3

Likelihood for errors on qubit 2 & 3

$$f(\Delta m_1) \times f(\sqrt{\pi} - \Delta m_2) \times f(\sqrt{\pi} - \Delta m_3)$$

By comparing the likelihoods for the error patterns, we can correct the double-error one

The likelihoods for qubit 2 & 3 are almost the same
Results for the three-qubit bit-flip code

- Our method can improve the QEC performance and reduce the squeezing level required for the failure probability $10^{-9}$ by 1.5 dB
- Our method can correct double errors on the three qubits
Results for the three-qubit bit-flip code

- Our method can improve the QEC performance and reduce the squeezing level required for the failure probability $10^{-9}$ by 1.5 dB.
- Our method can correct double errors on the three qubits.

![Graph showing failure probability vs. standard deviation of the GQC $\xi$. The graph compares the conventional method (blue line) and the proposed method (red line), with a highlighted difference of approximately 1.5 dB.](image)
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Examination of the required squeezing

To examine required squeezing level for large-scale QC, we numerically calculated the **hashing bound** for the GQC.
Examination of the required squeezing

To examine required squeezing level for large-scale QC, we numerically calculated the hashing bound for the GQC.

Hashing bound $\xi_{hb}$

The hashing bound is the maximum value of the condition that yields the non-zero quantum capacity.

Encoding ➔ GQC ➔ Decoding

Increasing the variance by $\xi^2$

The GQC has nonvanishing quantum capacity for $\xi < \xi_{hb}$
Achievable hashing bound for the GQC

The GQC has nonvanishing quantum capacity for \( \xi < \xi_{hb} \)

GKP qubit concatenated with CSS code + Binary information → \( \xi_{hb} \approx 0.555 \)

Achievable hashing bound

Achievable hashing bound for the GQC

Encoding → GQC → Decoding

Increasing the variance by $\xi^2$

The GQC has nonvanishing quantum capacity for $\xi < \xi_{hb}$

GKP qubit concatenated with CSS code + Binary information → $\xi_{hb} \sim .555$

Optimal method (Open problem) → $\xi_{max} \sim .607$

$\sim .607$ has been conjectured as the lower bound of quantum capacity for the GQC

Achievable hashing bound

Achievable hashing bound for the GQC \cite{5,10}

- **Encoding** → **GQC** → **Decoding**
  
  Increasing the variance by $\xi^2$

  The GQC has nonvanishing quantum capacity for $\xi < \xi_{hb}$

GKP qubit concatenated with CSS code + Binary information $\rightarrow \xi_{hb} \sim .555$

GKP qubit concatenated with CSS code + Binary information + **Analog information** (This work) $\rightarrow \xi_{max} \sim .607$

$\sim .607$ has been conjectured as the lower bound of quantum capacity for the GQC

\cite{5,10} D. Gottesman et al., Phys. Rev. A, 64, 012310 (2001)
\cite{10} J. Harrington et al., Phys. Rev. A 64, 062301 (2001)
Analog QEC for the C4/C6 code

We applied our method to the Knill's C4/C6 code [11] using a message passing algorithm proposed by Poulin [12,13].

\[ \lvert \tilde{\psi} \rangle_L \]

**Encoded Bell measurement**

\[ \lvert + \rangle_L \]
\[ \lvert 0 \rangle_L \]

**Encoded Bell state preparation**

\[ \text{GQC} \]

\[ \text{MLD} \]

\[ M_p \]

\[ M_q \]

\[ X \]
\[ Z \]
We applied our method to the Knill's $C_4/C_6$ code using a message passing algorithm proposed by Poulin.

Analog QEC for the C4/C6 code

We applied our method to the Knill's C4/C6 code [11] using a message passing algorithm proposed by Poulin [12,13]

\[ |\tilde{\psi}\rangle_L \rightarrow \text{GQC} \rightarrow |+\rangle_L \rightarrow |0\rangle_L \rightarrow \text{Encoded Bell state preparation} \rightarrow \text{Encoded Bell measurement} \rightarrow \text{MLD} \rightarrow \text{MLD : Maximum likelihood decision} \]

Convention method

\[ p = \int_{-\frac{\sqrt{\pi}}{2}}^{\frac{\sqrt{\pi}}{2}} dx \frac{1}{\sqrt{2\pi}\xi^2} \exp(-x^2/2\xi^2) \]

Likelihood for correct bit value

Likelihood for incorrect bit value

\[ 1 - p \]

Proposal

\[ f(\Delta m) = \frac{1}{\sqrt{2\pi}\xi^2} e^{-\Delta m^2/(2\xi^2)} \]

\[ f(\sqrt{\pi} - |\Delta m|) \]

\[ \xi^2 : \text{Noise level of GQC} \]

Results for the C4/C6 code

- Our method can improve the QEC performance and reduce the squeezing level required for fault-tolerant QC.

Results for the C4/C6 code

- Our method can improve the QEC performance and reduce the squeezing level required for fault-tolerant QC
- Our method can achieve the hashing bound $\sim \frac{555}{607}$ \cite{5, 10}

\[ \text{Conventional method} \]

- Level-1
- Level-2
- Level-3
- Level-4
- Level-5

\[ \text{Proposed method} \]

- Level-1
- Level-2
- Level-3
- Level-4
- Level-5

\[ \text{Failure probability} \]

\[ \text{Standard deviation of the GQC } \xi \]

\[ \sim 1 \text{ dB} \]

\[ \frac{555}{607} \]


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Analog QEC for the surface code

We applied our method to a surface code which is used to implement topological QC \[14,15\]

Errors are detected at the boundary of the error chain

From the boundary information, we need to decide the most likely error chain by using minimum-weight perfect match match algorithm


Results for the surface code

Our method can also improve the QEC performance and reduce the squeezing level required for Topological QC \cite{16}

\[ d = 5, d = 7, d = 9, d = 11, d = 13, d = 15 \]

\[ \text{Conventional method} \quad \text{Proposed method} \]

\[ \text{Standard deviation of the GQC } \xi \]

Our method can also improve the QEC performance and reduce the squeezing level required for Topological QC \cite{16}

\begin{itemize}
\item Conventional method
\item Proposed method
\end{itemize}

\begin{align*}
\text{Conventional method} & \quad \text{Proposed method} \\
\text{Standard deviation of the GQC } \xi & \quad \text{Standard deviation of the GQC } \xi
\end{align*}

\begin{align*}
\text{Failure probability} & \quad \text{Failure probability} \\
10^{-1} & \quad 10^{-1} \\
10^{-2} & \quad 10^{-2} \\
10^{-3} & \quad 10^{-3}
\end{align*}

\begin{align*}
\text{Distance } d = 5 & \quad \text{Distance } d = 7 \\
\text{Distance } d = 9 & \quad \text{Distance } d = 11 \\
\text{Distance } d = 13 & \quad \text{Distance } d = 15
\end{align*}

\cite{16} K.F, K. Fujii, A. Tomita, and A. Okamoto (in preparation)
Summary

- The GKP qubit is a promising element toward large-scale QC

- Proposal to harness analog information contained in the GKP qubit to reduce the requirement for large-scale QC

- Proposal can achieve the hashing bound for the optimal method against the GQC

- Our method can be applied to various QEC codes such as, concatenated code, non-concatenated code, and surface code
Thank you for your attention!