Magic States Distillation Using Δ-Toric (good qLDPC?).

David Ponarovsky

January 4, 2024

Let $|f\rangle$ be a codeword in C_X, and let X_g be the indicator that equals 1 if f has support on X_g, and 0 otherwise. Observes that applying $T^{\otimes}$ on $|f\rangle$ yilds the state:

$$\begin{aligned}
T^{\otimes n}|f\rangle = T^{\otimes n}|\sum_g X_g g\rangle &= \exp\Big(i\pi/4\sum_g X_g|g| - 2\cdot i\pi/4\sum_{g,h} X_g X_h|g\cdot h| \\
&+ 4\cdot i\pi/4\sum_{g,h} X_g X_h X_l|g\cdot h\cdot l| - 8\cdot i\pi/4\cdot \text{ integers }\Big)|f\rangle \\
&= \exp\Big(i\pi/4\sum_g X_g|g| - 2\cdot \pi/4\sum_{g,h} X_g X_h|g\cdot h| + 4\cdot i\pi/4\sum_{g,h} X_g X_h X_l|g\cdot h\cdot l|\Big)|f\rangle
\end{aligned}$$

1 Many to One.

Assume that f is supported on exactly one generator. Then we have that $T^{\otimes n}|f\rangle = e^{i\pi|g|/4}|f\rangle$ Therefore, if $|g| = 4k+1$ then we are done.

2 Using Quntum Error Correction Codes.

Now assume that the code C_X is the quantum Tanner code, denote by G, A, B the group and the two generator sets that are used for constructing the square complex.

Claim 2.1. *Consider g, h that are supported on the same $v \in V$. We will call such a pair a source-sharing pair. Suppose that for any we have that $|g\cdot h|$ is even. Then there is a Clifford gate that computes* $|f\rangle \mapsto \exp\Big(-i\pi\sum_{g,h \textit{ source-sharing}} X_g X_h|g\cdot h|\Big)|f\rangle$.

3 Fail Attempt.

In addition, let us assume the existence of $d \in G$ such that d is non-identity and commutes with any element in $A \cup B$. Then, observe that multiplying by d preserves adjacency on the complex. Namely, if $\{u, v\} \in E$ then also $\{du, dv\} \in E$.

Consider $|f\rangle$ such that if X_g is not zero, and g is associated with a local codeword $c \in C_A \otimes C_B$ on vertex v, then the generator associated with the local codeword c on vertex $d\cdot v$ also supports f, denoted by g'. Thus, the exponent above becomes:

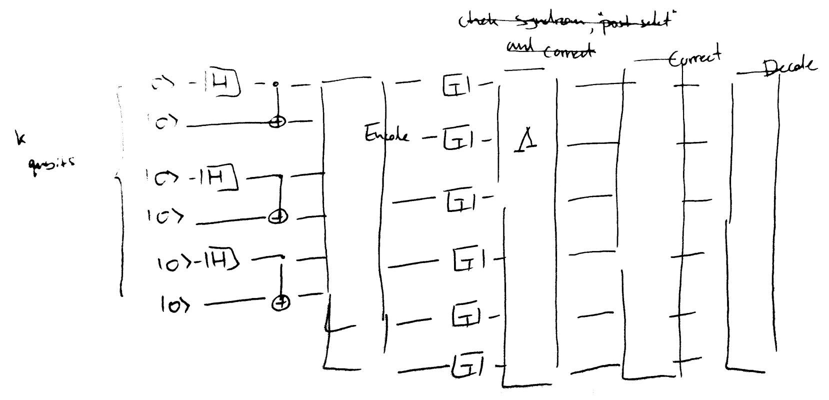

Figure 1: Quantum Circuit for distillation.

$$= \exp\Big(i\pi/4 \sum_g X_g|g| - 2\cdot\pi/4 \sum_{g,h\in G/a} X_gX_h|g\cdot h| + X_{g'}X_{h'}|g\cdot h|$$

$$+ 4\cdot i\pi/4 \sum_{g,h\in G/a} X_gX_hX_l|g\cdot h\cdot l| + X_{g'}X_{h'}X_{l'}|g\cdot h\cdot l|\Big)\,|f\rangle$$

$$= \exp\Big(i\pi/4 \sum_g X_g|g| - 2\cdot 2\cdot\pi/4 \sum_{g,h\in G/a} X_gX_h|g\cdot h| + 2\cdot 4\cdot i\pi/4 \sum_{g,h\in G/a} X_gX_hX_l|g\cdot h\cdot l|\Big)\,|f\rangle$$

$$= \exp\Big(i\pi/4 \sum_g X_g|g| - i\pi \sum_{g,h\in G/a} X_gX_h|g\cdot h|\Big)\,|f\rangle$$

Claim 3.1. *The gate* $|f\rangle \mapsto \exp\Big(-i\pi\sum_{g,h\in G/a} X_gX_h|g\cdot h|\Big)\,|f\rangle$ *is in the Clifford.*

Proof. Just decode f and apply **CZ** between any pair of qubits corresponding to the generators g, h such that $g\cap h = 1$. Then encode the state again. Observes that **CZ** is a Clifford gate, and by the fact that the code is a CSS code then the decoder and the encoder are both in the Clifford. □

Let's denote the circuit defined in Claim 3.1 by Λ. So we have that:

$$\Lambda^\dagger \exp\Big(i\pi/4 \sum_g X_g|g| - i\pi \sum_{g,h\in G/a} X_gX_h|g\cdot h|\Big)\,|f\rangle$$
$$= \exp\Big(i\pi/4 \sum_g X_g|g|\Big)\,|f\rangle$$

Maybe what do we need is to arrange in some way $|g| + |g'| = 4k+1$ and $\langle g, f\rangle = \langle g', f'\rangle$

Claim 3.2. *For any m codewords $x_1..x_m$ there is a set of coordinates I and $|I| < \alpha n$. Such that:*

$$\sum_{j\in[n]/I} x_a^j x_b^j = 0$$

For any pair x_a, x_b.

Claim 3.3. *For any m codewords $x_1..x_m$ there is a set of coordinates I and $|I| < \alpha n$. Such that:*

$$\sum_{a,b,j\in[n]/I} x_a^j x_b^j = 4k$$

For any pair x_a, x_b.

Claim 3.4. *Let C be a code at rate $\rho(C) > 7/8$ has at least one codeword $x \in C$, such that $|x| =_8 1$.*

Definition 3.1. *We will say that a code C is (l, m)-genorthogonal if there exists a generator set G for C such that for any $I \subset G$ such that $1 < |I| < l$ we have that:*

$$\sum_{i\in[n]} \prod_{g_j \in I \subset G} g_j^i =_m 0$$

Claim 3.5. *If there exists a single (l, m)-genorthogonal code for a finite length Δ, then there is a family of (l, m)-genorthogonal good codes. Moreover, if there exists a generator in C_0 of weight $|\cdot|_m = 1$, then there exists a family that also has at least one generator of weight $|\cdot|_m = 1$.*

Proof. Denote by $C_0 = \Delta[1, \rho_0, \delta_0]$ an (l, m)-genorthogonal code and observes that for any $C = [n, \rho n, \delta n]$ the tensor code $C_0 \otimes C = [\Delta n, \rho_0 \rho \Delta n, \delta_0 \delta \Delta n]$ is also (l, m)-genorthogonal code.

For the seconed part of the claim, Choose C to be a good code with rate $> (2^m - 1)/2^m$ by Claim 3.4 there is at least on codeword c in C such that $|c| =_m 1$.

So pick the base for $C_0 \otimes C$ such the first generator is $g_0 \otimes c$ where g_0 denote a generator of C_0 satisfies $|g_0| =_m 1$. Then $|g_0 \otimes c| = |g_0| \cdot |c| =_m 1$. □

Claim 3.6. *Let C be a ρ-rate, $(11, 8)$-genorthogonal code such the generators set contains generator c at weight $|c|_8 = 1$. Then there is a generators set G' for C such that C is $(2, 8)$-genorthogonal in respeect to G' and there are at least $\rho/8$ generators $g \in G$ at weight $|g| =_8 1$.*

Proof. If C has more than $\rho/8 \cdot n$ generators at weight $|\cdot| =_8 1$ then we done. Otherwise by pigeonhole principle we have a i such that more than $\rho/8$ portion of the generators are at weight $|\cdot| =_8 i$. Denote them by $g_1, g_2, g_3..g_m$. On the otherhand by Claim 3.4 there is in C at least one codewored c such that $|c| =_8 1$. Define the set $g_1^{'}, g_2'..g_m'$ as

$$g_t' = c + \sum_{j=t}^{t+10} g_j$$

$$\Rightarrow |g_{t+1}'| = |c| + \sum_t |g_j| + \sum_{|I|<10} \left| \prod_{g \in I \cup \{c\}} \alpha_\star g \right|$$

$$=_8 c + 8 \cdot i =_8 c =_8 1$$

On the otherhand:

$$|g_t g_{t'}| = \frac{1}{2}|g_t| + g_{t'}| - |g_t| + |g_{t'}| - 2|g_t|$$

¡++¿ □

Claim 3.7. *There exists, a good LDPC code (classic) C such that $C^\perp$ is also a good code and a generator set G:*

1. *For any pair $x \neq y \in G \to x \cdot y = 0$*
2. *For any triple $x \neq y, z \in G \to \sum_i x_i y_i z_i = 0$*
3. *There exists $\rho' > 0$ such that one can choose a generator set G satisfying that at least ρ' portion of its generators g have weight $|g| = 8k + 1$.*

Claim 3.8. *Let C_0 be a Triorthogonal code of constant length Δ. Let $C_1 = [n, \rho n, \delta n]$ be a good LDPC code with rate $> 7/8$ such that $C^\perp$ is also a good code. Denote by C the hyperproduct code obtained by multiplying the tensor code defined by them. Namely:*

$$C = (C_1 \otimes C_0) \times_H (C_1 \otimes C_0)$$

Then there is an efficient circuit for $2\Delta n \to (\rho_0 \rho/8)\Delta n$ magic states distillation with asymptotic overhead approaching 1