Magic States Distillation Using Quantum LDPC Codes.

David Ponarovsky

March 14, 2024

1 Good Codes With Large Λ.

Claim 1.1. *Let* $v_1, v_2..v_k$ *vectors in* $\mathbb{F}_2^n$, *then there are* $u_1, u_2..u_{k'}$ *for* $k' > k/2$. *Such* $span\,\{u_1, u_2..u_{k'}\} \subset$ *span* $\{v_1, v_2..v_k\}$ *and for any* i, j *it holds that* $u_i u_j = 0$.

<div>

1 Let $J \leftarrow \emptyset$
2 **for** $i \in [k/2]$ **do**
3 $\quad$ $J \leftarrow J \cup \{v_{2i-1}, v_{2i}\}$
4 $\quad$ **for** $S \subset J$ **do**
5 $\quad\quad$ Compute the vector m_S
6 $\quad\quad$ define as $m_{S,j} = u_j \sum_{w \in S} w$
7 $\quad$ **end**
8 $\quad$ Pick S such $m_S = 0$ and set
$\quad\quad$ $u_i \leftarrow \sum_{w \in S} w$
9 $\quad$ Choose randomly $w \in S$ and set
$\quad\quad$ $J \leftarrow J/w$
10 **end**
$\quad$: Find commuted vectors $u_1, u_2, ..u_{k'}$

</div>

<div>

1 Let $J \leftarrow \emptyset$
2 **for** $i \in [k/3]$ **do**
3 $\quad$ $J \leftarrow J \cup \{v_{3i-2}, v_{3i-1}, v_{3i}\}$
4 $\quad$ **for** $S \subset J$ **do**
5 $\quad\quad$ Compute the vector m_S
6 $\quad\quad$ define as
$\quad\quad$ $m_{S,j,j'} = u_{j'} u_j \sum_{w \in S} w$
7 $\quad$ **end**
8 $\quad$ Pick S such $m_S = 0$ and set
$\quad\quad$ $u_i \leftarrow \sum_{w \in S} w$
9 $\quad$ Choose randomly $w \in S$ and set
$\quad\quad$ $J \leftarrow J/w$
10 **end**
$\quad$: Find commuted vectors $u_1, u_2, ..u_{k'}$

</div>

Proof. Consider Algorithm 1a, We are going to prove that at line number (8) the alg always finds a subset S that satisfies the equality. Assume not. On one hand, the number of possible values that m_S can have is $2^i - 1$. On the other hand, since J contains $i + 1$ vectors on the ith iteration, it follows that the number of subsets is $2^{i+1} - 1 \geq 2^i$.

Therefore, there must be at least two different subsets S and S' such that $u_S = u_{S'}$. However, this means that

$$m_{S \Delta S', j} = u_j \sum_{w \in S \Delta S'} w = u_j \left(\sum_{w \in S \Delta S'} w + 2 \sum_{w \in S \cap S'} w \right)$$
$$= m_{S,j} + m_{S',j} = 0$$

Thus, $m_{S \Delta S'} = 0$. Additionally, it is clear that the rank does not decrease, as for u_i, there exists one v_j such that only u_i is supported by v_j. $\qquad\square$

Claim 1.2. *Let* $v_1, v_2..v_k$ *vectors in* $\mathbb{F}_2^n$ *and* m *be an integer* $m < k$, *then there are* $u_1, u_2..u_{k'}$ *for* $k' > k/2 - m$. *Such* *span* $\{u_1, u_2..u_{k'}\} \subset$ *span* $\{v_{m+1}, v_{m+2}..v_k\}$, *for any* i, j *it holds that* $u_i u_j = 0$ *and for any* $i \in]k'$, $j \leq m$ *it holds that* $u_i v_j = 0$.

Proof. Modify the Algorithm 1a as follows, Initialize $u_1, .u_m$ to be $v_1, .., v_m$ and $J = \{v_{m+1}, ..v_{2m+2}\}$. Notice that in the ith iteration, for the counting argument to works in the proof of Claim 1.1, we have to ensure that:

$$|J| \geq m + i + 1, \text{ So } m + i + 1 \leq k - m - i$$
$$\Rightarrow i \leq k/2 - m - \frac{1}{2}$$

In the end, $u_{m+1}, u_{m+2}, .., u_{k'}$ will satisfy the equations. $\qquad \square$

Claim 1.3. *Let $v_1, v_2..v_k$ vectors in $\mathbb{F}_2^n$, then there are $u_1, u_2..u_{k'}$ for $k' > k/4$. Such span $\{u_1, u_2..u_{k'}\} \subset$ span $\{v_1, v_2..v_k\}$. And for any $i, j \sum u_{i,k}u_{j,k} =_4 0$.*

Proof. Use the Algorithm 1a twice. However, in the second iteration, define $m_{S,j}$ to be the product of module 4. Note that $m_{S,j}$ must be either $4n$ or $4n + 2$. Thus, we can follow the proof of Claim 1.1. $\qquad \square$

Claim 1.4. *[COMMENT] Complete for the above the version, which handle triples. number of options is $\left(2^i\right)^2 = 2^{2i}$ and therefore we have the correctness if $|J| > 2i + 1$.*

Claim 1.5. *Consider the Left-Right (Δ,n)-Complex Γ. $\dim C_X/C_Z^\perp \cap C_Z/C_X^\perp$ is linear in n.*

Proof. The rates of both $C_X/C_Z^\perp$ and $C_Z^\perp/C_X^\perp$ are $(2\rho - 1)^2$, where ρ can be any number in the range $(0, 1)$ [LZ22]. Consider choosing ρ such that the rates of the quotient spaces are strictly greater than $\frac{1}{2} + \alpha$. This implies that the rate of their intersection is greater than 2α. $\qquad \square$

Corollary 1.1. *Fix the rate of the small codes C_A and C_B to $\rho = \frac{1}{2} + \alpha$. There is a subspace $\Lambda \subset C_X/C_Z^\perp$ at rate $\frac{1}{4} \cdot 2\alpha$ such that for any $x \in \Lambda$ and $y, z \in C_Z^\perp \cup \Lambda$ it holds that:*

1. $xy =_4 0$

2. $xyz =_4 \sum_i x_i y_i z_i =_4 0$

Claim 1.6. *Consider C, Λ and C', Λ' defined in ??. Denote by $\bar{\Lambda}$ the subspace C/Λ. Then:*

$$d(C'/\bar{\Lambda}') \geq d(C/\bar{\Lambda})$$

Proof. The way we perform Guess elimination is critical. We want to make sure that we do not add an Λ row to a $\bar{\Lambda}$ row. **[COMMENT]** Continue, Easy. Just need to perform the row reduction when rows of Λ at bottom, and then rotate the matrix $\curvearrowright$

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} \curvearrowright \begin{bmatrix} D & C \\ B & A \end{bmatrix}$$

$\qquad \square$

Claim 1.7 (Not Formal). *It is easy to see that by using concatenation again, one can obtain the code $\dim \Lambda' \leftarrow \frac{1}{2}\dim \Lambda'$. For any $x \in$ gen Λ', $|x|_4 = 1$, and for any $x \in C'/\Lambda'$, we have $|x|_4 = 0$.*

Proof. **[COMMENT]** We will do it by iterating the generators of C after performing rows reduction to the generator matrix. Now we will concatenate the i coordinate to complete the weight of the ith row to satisfy the requirements. $\qquad \square$

2 Compute $|C_Z^\perp\rangle$ In Constant Depth.

Let C_0 be a Δ-length error linear binary code, Γ a Δ-regular bipartite graph, and let C_Z be the Tanner code defined by C_0 and Γ. We are about to prove that the uniform superposition over $C_Z^\perp$ codewords can be computed at a depth dependent only on Δ, in particular independent of the $C_Z^\perp$-length. For this, we are going to use Proposition 10 in [MN98], which states that both the encoder and the decoder of any stabilizer m-length code can be implemented by a circuit at depth $\Theta(\log m)$ with $\Theta(m^2)$ ancillae.

Claim 2.1. *Let G be a Δ-regular bipartite graph, and denote by $C_Z^\perp$ the dual-tanner code $\mathcal{T}(G, C_0^\perp)^\perp$. Then there is a circuit that computes the state $|C_Z^\perp\rangle$ at $\Theta(\log \Delta)$ depth, and $\Theta(\Delta^2)n$ ancillary qubits.*

Proof. Let E_v and D_v be the encoder and the decoder of C_0 over the local view of vertex v, By [MN98] we have that both have depth $\Theta(\log \Delta)$ and require Δ^2 ancillae. Since Γ is bipartite, we can decompose V into V^- and V^+ such that the local views of any two vertices in $V^\pm$ are disjoint. Therefore, for any two different vertices $v, u \in V^\pm$, the encoders E_v and E_u act on disjoint subsets of qubits, each corresponding to the local view of either v or u. Consider the following algorithm:

1 Initialize $2n$ qubits.
2 Call the left and right segments L and R.
3 Apply E_v in parallel on L for any $v \in V^+$.
4 Apply E_v in parallel on R for any $v \in V^-$.
5 XOR R into L by applying CNOT from the ith bit of R to the ith bit of L.
6 Apply D_v in parallel on R for any $v \in V^-$.

Algorithm 1: Compute $|C_Z^\perp\rangle$

For any $v \in V$, let $|z_v\rangle$ be the superposition of codewords in C_0 supported by the local view of v. Similarly, for any subset of vertices $W \subset V$, let $|z_W\rangle$ be the uniform superposition over the subspace spanned by the generators supported by the vertices in W. In other words:

$$|z_W\rangle = |\sum_{v \in W} z_v\rangle$$

Using the notation, applying the encoders E_v, E_u for any pair of vertices with disjoints local view become:

$$E_v \cup E_u |0\rangle^n = E_v |0 + z_u\rangle = E_v |0\rangle|_{/u\text{'s view}} |z_u\rangle$$
$$= |z_v\rangle |z_u\rangle = |z_u + z_v\rangle$$

¡++¿ So applying all the encoders E_v at once over the positive vertices results in:

$$\left(\cup_{v \in V^+} E_v\right) |0\rangle^n = \left(\cup_{v \in V^+/v_0} E_v\right) |z_{v_0} + 0\rangle = |z_{V^+}\rangle$$

Thus the whole computation sum up into:

$$\left(\cup_{v \in V^+} E_v\right) \otimes \left(\cup_{v \in V^+} E_v\right) \qquad |0\rangle^n \otimes |0\rangle^n \mapsto$$
$$\text{CNOT} \qquad |z_{V^+}\rangle |z_{V^-}\rangle \mapsto$$
$$I \otimes \left(\cup_{v \in V^-} D_v\right) \qquad |z_{V^+} + z_{V^-}\rangle |z_{V^-}\rangle \mapsto$$
$$|z_{V^+} + z_{V^-}\rangle |0\rangle$$

$\square$

3 Distillate $|\Lambda + C_Z^\perp\rangle$ Into Magic.

Let $|f\rangle$ be a codeword in C_X, and let $\hat{X}_g$ be the indicator that equals 1 if f has support on generator g, and 0 otherwise. Observe that applying $T^\otimes$ on $|f\rangle$ yields the state:

$$T^{\otimes n} |f\rangle = T^{\otimes n} |\sum_g \hat{X}_g g\rangle = \exp\left(i\pi/4 \sum_g \hat{X}_g |g| - 2 \cdot i\pi/4 \sum_{g,h} \hat{X}_g \hat{X}_h |g \cdot h|\right.$$
$$\left. + 4 \cdot i\pi/4 \sum_{g,h} \hat{X}_g \hat{X}_h \hat{X}_l |g \cdot h \cdot l| - 8 \cdot i\pi/4 \cdot \text{ integers }\right) |f\rangle$$
$$= \exp\left(i\pi/4 \sum_g \hat{X}_g |g| - 2 \cdot \pi/4 \sum_{g,h} \hat{X}_g \hat{X}_h |g \cdot h| + 4 \cdot i\pi/4 \sum_{g,h} \hat{X}_g \hat{X}_h \hat{X}_l |g \cdot h \cdot l|\right) |f\rangle$$

So in our case:

$$T^{\otimes n} \left| f \right\rangle =$$

$$= \exp\Big(i\pi/4 \sum_{g \in \text{ gen } \Lambda} \hat{X}_g$$

$$- 2 \cdot \pi/4 \sum_{g,h \in \text{ gen } C_Z^\perp} \hat{X}_g \hat{X}_h |g \cdot h|$$

$$+ 4 \cdot i\pi/4 \sum_{g,h \in \text{ gen } C_Z^\perp} \hat{X}_g \hat{X}_h \hat{X}_l |g \cdot h \cdot l| \Big) \left| f \right\rangle$$

So eventually, we have a product of gates when non-Clifford gates are applied on only on generators of $C_Z^\perp$.

$$T^n \left| f \right\rangle = \prod_{g \in \text{ gen } \Lambda} T_g \prod_{g,h \in \text{ gen } C_Z^\perp} \{CS_{g,h}|CZ_{g,h}|I\} \prod_{g,h,l \in \text{ gen } C_Z^\perp} \{CCZ_{g,h,l}|I\} \left| f \right\rangle$$

Decompose $f = f_1 + f_2$, where f_1 is supported only on $C_X/C_Z^\perp$ and f_2 is supported only on $C_Z^\perp$. By using commuting relations, the above can be turned into.

$$T^n \left| f \right\rangle = \prod_{g \in \text{ gen } \Lambda} T_g \; X_{f_1}$$

$$\prod_{g,h \in \text{ gen } C_Z^\perp} \{CS_{g,h}|CZ_{g,h}|I\} \prod_{g,h,l \in \text{ gen } C_Z^\perp} \{CCZ_{g,h,l}|I\} \left| f_2 \right\rangle$$

Denote by M_1, M_2 the gates:

$$M_1 = \prod_{g \in \text{ gen } \Lambda, h} \{CZ_{g,h}|I\}$$

$$M_2 = \prod_{g,h \in \text{ gen } C_Z^\perp} \{CS_{g,h}|CZ_{g,h}|I\} \prod_{g,h,l \in \text{ gen } C_Z^\perp} \{CCZ_{g,h,l}|I\}$$

And then we get that

$$\prod_{g \in \text{ gen } \Lambda} T_g \left| f \right\rangle = M_1^\dagger T^n M_2^\dagger \left| f \right\rangle$$

$$\prod_{g \in \text{ gen } \Lambda} T_g \left| f \right\rangle = M_1^\dagger T^n \; E \; L[M_2^\dagger] \; \left| L[f] \right\rangle$$

Claim 3.1. *Let $v \in V^-$, and let g_1 be the generator supported by v, which matches an assignment of a codeword in $C_A \otimes C_B$ on the local view of v. Denote by U_{v,g_1} the control-gate which, depending on the control bit $(v,1)$, turns on g_1 over the edges associated with the local view of v in the graph G. Then, the depth of U_{v,g_1} depend only on Δ.*

Claim 3.2. *Let (v, g_1) and (u, g_2) be control wires for two different generators in the graph G. Then U_{v,g_1} and U_{u,g_2} **[COMMENT]** There must be a claim about the relationship between two different generators intersection, But I don't sure exactly why.*

Definition 3.1. *We say that a quantum circuit $\mathcal{C}$ is well error spreading if the light cone define by any T.*

Claim 3.3. *The state:*

$$\sum_{z \in C_Z^\perp} \exp\Big(-2 \cdot \pi/4 \sum_{g,h \in \text{ gen } C_Z^\perp} \hat{X}_g \hat{X}_h |g \cdot h|$$

$$+ 4 \cdot i\pi/4 \sum_{g,h \in \text{ gen } C_Z^\perp} \hat{X}_g \hat{X}_h \hat{X}_l |g \cdot h \cdot l| \Big) |z\rangle$$

Can be computed such that any

Proof. Denote by U_v the gate which turn on all the generators supported on v. As any of them is just of a code word of $C_A \otimes C_B$, namely turning on generator require touching at most constant number of qubits combing $\qquad\square$

Claim 3.4. *The state $\left(M_2^\dagger \otimes I \right) |C_Z^\perp + \Lambda\rangle |0\rangle$ can be computed, such that the light cone depth of any non-clifford gate is bounded by constant.*

Proof.

$$(I \otimes H_X)\, CX_{n \to n}\, (E \otimes E)\; I \otimes L[M_2^\dagger] \prod_{\substack{J \in \{ \text{ gen } \Lambda, \\ \text{gen } C_Z^\perp \}}} \prod_{g \in J} \left(I + X_{L[g]} \right) \qquad |0\rangle |0\rangle$$

$$= (I \otimes H_X)\, CX_{n \to n} \sum_{\substack{z \in C_Z^\perp \\ x \in \Lambda}} e^{\varphi(z)} \qquad |x\rangle |z\rangle$$

$$= \sum_{\substack{z \in C_Z^\perp \\ x \in \Lambda}} e^{\varphi(z)} \qquad |x + z\rangle |0\rangle$$

$$= \sum_{\substack{z \in C_Z^\perp \\ x \in \Lambda}} \left(M_2^\dagger \otimes I \right) \qquad |x + z\rangle |0\rangle$$

$$= \left(M_2^\dagger \otimes I \right) \qquad |C_Z^\perp + \Lambda\rangle |0\rangle$$

$$\square$$

Denote by $p \in [0, 1]$ the error rate of input magic states, and let $|A\rangle$ be an ancilla initialized to a one-qubit magic state. This $|A\rangle$ can be used to compute the T gate, with a probability of Z error occurring with a probability of p [BH12].

Claim 3.5. *There are constant numbers ζ_Δ, ξ_Δ, and a circuit $\mathcal{C}$ such that:*

1. *In the no-noise setting, The circuit compute the state*

$$\mathcal{C} |0\rangle^{\Theta(n)} \otimes |A\rangle^{\Theta(n)} \rightarrow \prod_{g \in \, gen \, \Lambda} T_g |C_Z^\perp + \Lambda\rangle$$

2. *Otherwise, the circuit computes the state*

$$\mathcal{C} |0\rangle^{\Theta(n)} \otimes |A\rangle^{\Theta(n)} \rightarrow Z^e \prod_{g \in \, gen \, \Lambda} T_g |C_Z^\perp + \Lambda\rangle$$

, where the probability that $e_i = 1$ is less than $\zeta_\Delta \cdot p$. Additionally, for any i, there are at most ξ_Δ indices j such that e_i and e_j are dependent.

Proof. Concatinate the $T^n \otimes I$ with the gate in Claim 3.4. $\qquad \square$

Claim 3.6. *For any $\alpha \in (0, 1)$ the probability that $|e| > (1 + \alpha)p\zeta_\Delta$ is less than:*

$$\mathbf{Pr} \left[|e| > (1 + \alpha)\mathbf{E}\left[|e|\right]\right] < \frac{1 \cdot \xi_\Delta n}{\alpha^2 \zeta_\Delta^2 p^2 n^2} = o\left(1/n\right)$$

Proof. By the Chebyshev inequality, notice that the number for which $\mathbf{E}\left[e_i e_j\right] - \mathbf{E}\left[e_i\right]\mathbf{E}\left[e_j\right] \neq 0$ is less than $\xi_\Delta n$. $\qquad \square$

Definition 3.2. *We will said that a decoder $\mathcal{D}$ for the good qunatum LDPC code is an good-local decoder if*

1. *There is a treashold μn such that if the error size is less than $|e| < \mu n$ then $\mathcal{D}$ correct e in constant number of rounds. With probability $1 - o(1/n)$.*

2. *In any rounds $\mathcal{D}$ performs at most $O(n)$ work (depth $\times$ width).*

3. *The above is true in operation-noisy settings, where there is a probability of p for an error to occur after acting on a qubit. $(\star)$*

$\star$ *The motivation for this is that if the decoder does not act on the qubit, then it also does not apply a T gate on it. Therefore, in the distillation setting, there is zero chance for an error to occur.*

Claim 3.7. *Suppose there is a good local decoder $\mathcal{D}$ for the good qLDPC code. Then, there exists p_0 such that for any sufficiently large n, there is a distillation protocol that, given $\Theta(n)$ magic states at an error rate $p < p_0$, successfully distills $\Theta(n)$ perfect magic states with a probability of $1 - o(1/n)$. Furthermore, the protocol's space and time complexity (both quantum and classical) are $\Theta(n)$ and $\Theta(n^2)$, respectively.*

References

[MN98]   Cristopher Moore and Martin Nilsson. *Parallel Quantum Computation and Quantum Codes*. 1998. arXiv: `quant-ph/9808027 [quant-ph]`.

[BH12]   Sergey Bravyi and Jeongwan Haah. "Magic-state distillation with low overhead". In: *Physical Review A* 86.5 (2012), p. 052329.

[LZ22]   Anthony Leverrier and Gilles Zémor. *Quantum Tanner codes*. 2022. arXiv: `2202.13641 [quant-ph]`.