Magic States Distillation Using Quantum LDPC Codes.

David Ponarovsky

March 6, 2024

1 Good Codes With Large Λ.

Definition 1.1. *Let $M \in \mathbb{F}_2^{k\times n}$ upper triangular matrix such that $k < n$. We say that M has the 1-stairs property if $M_{ij} = 1$ any $j < i$.*

$$\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 1 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 1 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 1 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 1 & \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix}$$

Claim 1.1. *Any $M \in \mathbb{F}_2^{k\times n}$ upper triangular matrix can be turn into upper triangular matrix that has the 1-stairs property by elementary operation.*

Proof. Consider the following algorithm: Let M be our initial matrix. We iterate over the rows from left to right. In the ith iteration, we check for any row $j < i$ if $M_{ji} = 1$. If not, we set M to be the matrix obtained by adding the ith row to the jth row. Since M is an upper triangular matrix, adding the ith row does not change any entry M_{js} for $s < i$. Therefore, the obtained matrix is still an upper triangular matrix and the entries at M_{js} for $j, s < i$ remain the same, namely 1 if and only if $j \leq s$.

Continuing with the process eventually yields, after k iterations, a matrix with the 1-stair property. □

Claim 1.2. *Let C be a $[n, k, d]$ binary linear code, and let Λ be subcode $\Lambda \subset C$ at dimension $k' > \alpha k$ for some $\alpha \in (0, 1)$. Then there exists a code $C' = [\leq 2n, \geq (1 - \alpha + \frac{\alpha^3}{24})k, d]$ and a subcode of it Λ' in it at dimension $\geq \frac{\alpha^3}{24}k$, such:*

1. *For every $x \in \Lambda'$ and $y \in C'$ $\;x \cdot y = 0$*
2. *For every $x \in \Lambda'$ and $y, z \in C'$ $\;x \cdot y \cdot z = 0$*

Proof. First, we can assume that the generator matrix of C is an upper triangular matrix, such that the first k' rows span Λ. Notice that after applying the algorithm from claim 1.1 starting from the first row and stopping at the k'th row, the first k' rows are kept in Λ. So let's assume that is the form of the generator matrix.

Now, let's consider the following process: going uphill, from right to left, starting at the k' row. Initially, set $j \leftarrow k'$ and in each iteration, advance it to be the index of the next row, namely $j \leftarrow j - 1$. In each iteration, ask how many rows G_m, such that $m \leq j$, satisfy $G_m G_j = 0$ and how many pairs of rows $G_m, G_{m'}$ such that $m, m' \leq j$ satisfy $G_m \cdot G_{m'} \cdot G_j = 0$. Denote by p the probability to fall on unsatisfied equation from the above.

- If $p \geq \frac{1}{2}$ then we move on to the next iteration.
- Otherwise, we encode the jth coordinate by C_0, which maps $1 \to w$ such that $w \cdot w = 0$. This flips the value of $G_m G_j$ for any pair and $G_m G_{m'} G_j$ for any triple such that $m, m' \leq j$, so we get that the majority of the equations are satisfied. Also notice that the concatenation doesn't change the value of any multiplication at the form $G_m G_{j'}$ for $j' > j$. Therefore, for any $j < j' \leq k'$ the number of the satisfied equations relative to j' is not changed, meaning it is still the majority.

  Set G to be the new matrix after the concatenation by C_0.

In the end of the process G is going to be the generator matrix of C'. It's left to construct Λ', we are going to do so by taking from the k' rows a subset that satisfies the desired property in Claim 1.2.

Let S be the set of rows among the first k' rows for which there is at least one unsatisfied equation. We will now prove that if k' is large enough, specifically linear in k, then $|S|$ is small enough to obtain Λ' by removing the rows in S.

Observe that the number of satisfied equations is at least:

$$\frac{1}{2}\left(k'-1+(k'-1)^2\right)+\frac{1}{2}\left(k'-1+(k'-1)^2\right)+\frac{1}{2}\left(k'-2+(k'-2)^2\right)+..+\frac{1}{2}\left(1+(1)^2\right)$$
$$=\frac{1}{2}\left(\binom{k'+1}{2}+\frac{k'(k'+1)(2k'+1)}{6}\right)$$

So

$$\begin{aligned}|S|\cdot k+|S|\cdot k^2 &\le k'\left(k+k^2\right)-\frac{1}{2}\left(\binom{k'+1}{2}+\frac{k'(k'+1)(2k'+1)}{6}\right)\\ \Rightarrow |S| &< k'-\frac{1}{2}\left(\frac{1}{k^2+k}\binom{k'+1}{2}+\frac{1}{k^2+k}\frac{k'(k'+1)(2k'+1)}{6}\right)\\ \Rightarrow |S| &< k'-\frac{k'^3}{24k^2}\end{aligned}$$

Therefore, if $k'\ge\alpha k$ we have that $|S|<(\alpha-\frac{\alpha^3}{24})k$ implies that $\dim\Lambda'\ge\frac{\alpha^3}{24}k$.

□

Claim 1.3. *Consider C,Λ and C',Λ' defined in Claim 1.2. Denote by $\bar{\Lambda}$ the subspace C/Λ. Then*

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

Claim 1.4 (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 $x\in\Lambda'$, $|x|_4=1$, and for any $x\in C'/\Lambda'$, we have $|x|_4=0$.*

[COMMENT] The argument above that the distance d' remain the same is not correct. Yet, if we are defining the distance of any codeword in $C/(C/\Lambda)$ to be greater than d' then we win. (The problem was that gauss elimination might change the wight of rows associate with Λ generators.

2 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 $\hat{X}_g$, and 0 otherwise. Observes that applying $T^{\otimes}$ on $|f\rangle$ yilds the state:

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

So in our case:

$$\begin{aligned}
T^{\otimes n}|f\rangle = & \\
&= \exp\Big(i\pi/4 \sum_{g\in\Lambda} \hat{X}_g \\
&- 2\cdot \pi/4 \sum_{g\in\Lambda, h} 2\hat{X}_g\hat{X}_h \\
&- 2\cdot \pi/4 \sum_{g,h\in \text{ gen } C_Z^{\perp}} \hat{X}_g\hat{X}_h|g\cdot h| \\
&+ 4\cdot i\pi/4 \sum_{g,h\in \text{ gen } C_Z^{\perp}} \hat{X}_g\hat{X}_h\hat{X}_l|g\cdot h\cdot l|\Big)|f\rangle
\end{aligned}$$

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

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

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.

$$\begin{aligned}
T^n|f\rangle = & \prod_{g\in\Lambda,h}\{CZ_{g,h}|I\} \prod_{g\in\Lambda} T_g \;\; X_{f_1} \\
& \prod_{g,h\in C_z^{\perp}}\{CS_{g,h}|CZ_{g,h}|I\} \prod_{g,h,l\in C_z^{\perp}}\{CCZ_{g,h,l}|I\}|f_2\rangle
\end{aligned}$$

Denote by M_1, M_2 the gates:

$$\begin{aligned}
M_1 &= \prod_{g\in\Lambda,h}\{CZ_{g,h}|I\} \\
M_2 &= \prod_{g,h\in C_z^{\perp}}\{CS_{g,h}|CZ_{g,h}|I\} \prod_{g,h,l\in C_z^{\perp}}\{CCZ_{g,h,l}|I\}
\end{aligned}$$

And then we get that

$$\begin{aligned}
\prod_{g\in\Lambda} T_g|f\rangle &= M_1^{\dagger}T^n M_2^{\dagger}|f\rangle \\
\prod_{g\in\Lambda} T_g|f\rangle &= M_1^{\dagger}T^n \;\; E \;\; L[M_2^{\dagger}] \;\; |L[f]\rangle
\end{aligned}$$

Claim 2.1. *The state* $\left(M_2^{\dagger}\otimes I\right)|C_Z^{\perp} + \textit{ span } \Lambda\rangle|0\rangle$ *can be computed, such that the light cone depth of any non-clifford gate is bounded by constant.*

Proof.

$$
\begin{aligned}
(I \otimes H_X)\, CX_{n\to n}\, (E \otimes E) \quad I \otimes L[M_2^\dagger] \prod_{\substack{J \in \{\Lambda,\\ \text{gen } C_Z^\perp\}}} \prod_{g \in J} \left(I + X_{L[g]}\right) & \quad |0\rangle\,|0\rangle \\
= (I \otimes H_X)\, CX_{n\to n} \sum_{\substack{z \in C_Z^\perp \\ x \in \text{ span } \Lambda}} e^{\varphi(z)} & \quad |x\rangle\,|z\rangle \\
= \sum_{\substack{z \in C_Z^\perp \\ x \in \text{ span } \Lambda}} e^{\varphi(z)} & \quad |x+z\rangle\,|0\rangle \\
= \sum_{\substack{z \in C_Z^\perp \\ x \in \text{ span } \Lambda}} \left(M_2^\dagger \otimes I\right) & \quad |x+z\rangle\,|0\rangle \\
= \left(M_2^\dagger \otimes I\right) & \quad |C_Z^\perp + \text{ span } \Lambda\rangle\,|0\rangle
\end{aligned}
$$

□

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 2.2. *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*

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

2. *Otherwise, the circuit computes the state*

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

   , 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 2.1. □

Claim 2.3. *For any $\alpha \in (0,1)$ the probability that $|e| > (1+\alpha)p\zeta_\Delta$ is less than:*

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

Proof. By the Chebyshev bound, 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 $\xi_\Delta n$. □

Definition 2.1. *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 2.4. *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

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