

# $\sqrt{n} \mapsto \Theta(n)$ Magic States 'Distillation' Using Quantum LDPC Codes.

David Ponnarovsky

August 15, 2024

## 1 The Construction.

Let  $x_0$  be a codeword of  $C_X/C_Z^\perp$ . Denote by  $w \in \mathbb{F}_2^n$  the binary string presents the  $Z$ -generator that anti commute with the  $X$ -generator corresponds to  $x_0$ . Let  $\mathcal{X} = \{x_0, x_1, \dots, x_{k'}\} \in \mathbb{F}_2^n$  be a subset of a base for the code  $C_X/C_Z^\perp$ . Such  $(\text{span } \mathcal{X}/x_0)|_w$  is Triorthogonal code. Let us denote by  $\mathcal{X}'$  the base  $\{y_1, y_2, \dots, y_{k'}\} \in \mathbb{F}_2^n$  defined such:  $y_i = x_j + x_0$ .

Denote by  $E$  the circuit that encodes the logical  $i$ th bit to  $y_i$ , by  $T^{(w)}$  the application of  $T$  gates on the qubits for which  $w$  act non trivial, means  $T^{(w)}$  is a tensor product of  $T$ 's and identity where on the  $i$ th qubit  $T^{(w)}$  apply  $T$  if  $w_i$  is 1 and identity otherwise. And finally by  $D$  denote the gate that decode binary strings in  $\mathbb{F}_2^n$  back into the logical space.

## 2 Proof of Theorem 1.

**Claim 2.1.** *There exists family of non-trivial distance quantum LDPC codes  $Q$  such the codes span  $\mathcal{X}'$  chosen respect to them has a positive rate. Furthermore, the rate of span  $\mathcal{X}'$  is asymptotically converges to  $Q$  rate:*

$$|\rho(Q) - \rho(\text{span } \mathcal{X}')| = o(1)$$

*Proof.* Let  $\Delta$  be a constant integer,  $C_0, \tilde{C}_0$  codes over  $\Delta$  bits such  $\tilde{C}_0$  is Triorthogonal and  $C_0$  contains  $\tilde{C}_0$ ,  $C_0$  has parameters  $\Delta[1, \delta_0, \rho_0]$ , and  $C_0^\top$  has relative distance greater than  $\delta_0$ . Let  $C_{\text{Tanner}}$  be a Tanner code, defined by taking an expander graph with good expansion and  $C_0$  as the small code. Let  $C_{\text{initial}}$  be the dual-tensor code obtained by taking  $(C_{\text{Tanner}}^\perp \otimes C_{\text{Tanner}}^\perp)^\perp$ . Notes that first this code has positive rate and  $\Theta(\sqrt{n})$  distance, second this code is an LDPC code as well. Notice also that  $C_{\text{initial}}^\top$  obtained by transporting the parity check matrix, and therefore equals to  $(C_{\text{Tanner}}^{\top, \perp} \otimes C_{\text{Tanner}}^{\top, \perp})^\perp$ . Hence  $C_{\text{initial}}^\top$  has a square root distance as well.

Let  $Q$  the CSS code, obtained by taking the Hyperproduct of  $C_{\text{initial}}$  with itself. So  $Q$  is an quantum qLDPC code with parameters  $[n, \Theta(n^{\frac{1}{4}}), \Theta(n)]$ . Pick  $x_0$  and  $w \in \mathbb{F}_2^n$ , which correspond to the supports of anti commute  $X$  and  $Z$  generators, such that  $w$  can be obtains by setting a codeword of  $C_{\text{Tanner}}$  on the first  $n^{\frac{1}{4}}$  bits and padding by zeros the rest. Clearly,  $|w| = \Theta(n^{\frac{1}{4}})$ .

Now for defying span  $\mathcal{X}$ , we are going to consider the parity checks matrix obtained by adding restrictions to  $C_X$  restrictions as follows: Divide the first  $w$  bits into  $\Delta$ -size buckets, define by  $w(i)$  the  $i$ th coordinate on which  $w$  isn't trivial, for example if  $w(1) = j$  then  $j$  is the first nonzero coordinate of  $w$ , Denote by  $B_1, B_2, \dots, B_{|w|/\Delta}$  the partion of  $w$ 's bits:

$$\begin{aligned} B_1 &= \{w(1), w(2), \dots, w(\Delta)\} \\ B_2 &= \{w(\Delta + 1), w(\Delta + 2), \dots, w(2\Delta)\} \\ B_i &= \{w((i-1)\Delta + 1), w((i-1)\Delta + 2), \dots, w(i\Delta)\} \end{aligned}$$

Then let  $\text{span } \mathcal{X}$  be all the codewords of  $C_X/C_Z^\perp$  satisfying  $\tilde{C}_0$  restrictions for each bucket, Let us name the union of  $\tilde{C}_0$  restrictions over the buckets by  $B$ . The dimension of the space satisfies both  $C_X$  restrictions and  $B$  is at least:

$$\rho(C_X) \cdot n - |B| \cdot (1 - \rho(\tilde{C}_0))\Delta \geq \rho(C_X) \cdot n - n^{\frac{1}{4}}/\Delta$$

And by the fact that the dimension of  $C_Z^\perp$ 's codewords satisfying  $B$  is strictly lower then  $\dim C_Z^\perp$ , we get the following lower bound:

$$\begin{aligned} \dim \mathcal{X} &\geq \rho(C_X) \cdot n - n^{\frac{1}{4}}/\Delta + \rho(C_Z) \cdot n - n \\ &\geq \rho(Q) - n^{\frac{1}{4}}/\Delta \end{aligned}$$

□

**Claim 2.2.** *Let  $|\mathcal{X}'\rangle \propto \sum_{x \in \text{span } \mathcal{X}'} |x\rangle$ . Then  $T^{(w)} |\mathcal{X}'\rangle \propto \sum_{x \in \text{span } i} x$*