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

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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 $\mathcal{X} = \{x_0, x_1, ..x_{k'}\} \in \mathbb{F}_2^n$ be a subset of a base for the code $C_X/C_Z^{\perp}$. Such (span $\mathcal{X}/x_0$)$|_w$ is Triorthogonal code. Let us denote by $\mathcal{X}'$ the base $\{y_1, y_2, .., y_{k'}\} \in \mathbb{F}_2^n$ defined such: $y_i = x_j + x_0$.

Denote by E the circuit that encodes the logical ith 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 ith 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 a asymptotically converges to Q rate:*

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

Proof. Let Δ be a constant integer, $C_0, \tilde{C}_0$ codes over Δ 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 δ_0. Let C_{Tanner} be a Tanner code, defined by taking an expander graph with good expansion and C_0 as the small code. Let C_{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_{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_{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 Δ-size buckets, define by $w(i)$ the ith coordinate on which w isn't trivial, for example if $w(1) = j$ then j is the first nonzero coordinate of w, Denote by $B_1, B_2, .., B_{|w|/\Delta}$ the partion of w's bits:

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

Then let 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:

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

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:

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

Since $\mathcal{X}'$ is given by taking $x_0 + \mathcal{X}$ we get the required lower bound while it's easy to see that upper bound gotten immediately.. $\square$

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