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Constant Overhead Quantum Fault Tolerance with Quantum Expander Codes

By Omar Fawzi, Antoine Grospellier, and Anthony Leverrier

Abstract

The *threshold theorem* is a seminal result in the field of quantum computing asserting that arbitrarily long quantum computations can be performed on a *faulty* quantum computer provided that the noise level is below some constant threshold. This remarkable result comes at the price of increasing the number of qubits (quantum bits) by a large factor that scales polylogarithmically with the size of the quantum computation we wish to realize. Minimizing the space overhead for fault-tolerant quantum computation is a pressing challenge that is crucial to benefit from the computational potential of quantum devices.

In this paper, we study the asymptotic scaling of the space overhead needed for fault-tolerant quantum computation. We show that the polylogarithmic factor in the standard threshold theorem is in fact not needed and that there is a fault-tolerant construction that uses a number of qubits that is only a constant factor more than the number of qubits of the ideal computation. This result was conjectured by Gottesman who suggested to replace the concatenated codes from the standard threshold theorem by quantum error-correcting codes with a constant encoding rate. The main challenge was then to find an appropriate family of quantum codes together with an efficient classical decoding algorithm working even with a noisy syndrome. The efficiency constraint is crucial here: bear in mind that qubits are inherently noisy and that faults keep accumulating during the decoding process. The role of the decoder is therefore to keep the number of errors under control during the whole computation.

On a technical level, our main contribution is the analysis of the **SMALL-SET-FLIP** decoding algorithm applied to the family of *quantum expander codes*. We show that it can be parallelized to run in constant time while correcting sufficiently many errors on both the qubits and the syndrome to keep the error under control. These tools can be seen as a quantum generalization of the **BIT-FLIP** algorithm applied to the (classical) expander codes of Sipser and Spielman.

1. INTRODUCTION

Quantum computers are expected to offer significant, sometimes exponential, speedups compared to classical computers. For this reason, building a large, universal quantum computer is a central objective of modern science.

Despite two decades of effort, experimental progress has been somewhat slow and the largest computers available at the moment reach a few tens of physical qubits, still quite far from the numbers necessary to run “interesting” algorithms. A major source of difficulty is the extreme fragility of quantum information: storing a qubit is very challenging, but processing quantum information even more so.

Any physical implementation of a quantum computer is unavoidably imperfect because qubits are subject to decoherence and physical gates can only be approximately realized. In order to compute the outcome of an ideal circuit C using imperfect qubits and gates, the idea is to transform C into another circuit C' , which gives the same outcome with high probability, even if its components are noisy. It is common to refer to the gates or wires of the circuit C as *logical* gates or wires and to those of C' as the *physical* ones.

1.1. Fault-tolerant classical computation

The idea of constructing reliable circuits from unreliable components goes back to von Neumann²⁵ and we briefly sketch the construction he proposed. Given an ideal classical circuit C computing a Boolean function, we construct C' by duplicating each wire and each gate m times. For example, suppose we have an AND gate between wires w_1 and w_2 in C . Then, we will associate to the logical wires w_b in C , m physical wires $w_{b,i}$ for $i \in \{1, \dots, m\}$, and the logical AND will be implemented by m physical AND gates between wires $w_{1,i}$ and $w_{2,i}$. Then, the output of C' is defined as the majority applied to the m wires corresponding to the output of C . If the components of C' are perfect, we can see C' as a version of C where each wire is encoded in a simple error-correcting code: the m -repetition code. If the components of C' are now noisy, then the m wires will generally take different values. As each gate can potentially propagate errors, it is important to correct for errors regularly. If we could apply perfect gates, this would be easy: we simply apply a majority vote among the m wires. Interestingly, von Neumann showed the existence of a circuit that reduces errors even with noisy gates and he called it a “restoring organ.” This is done by applying majorities not on all the m wires but on well-chosen subsets using a concentrator; see Pippenger¹⁶ for details. As the probability that the majority of a block of m wires takes the wrong value is exponentially small in m , it is sufficient to

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choose $m = O(\log s)$ to ensure that all the components of the circuit work as expected with high probability. Here, s is the number of gates in the original circuit C . Thus, starting with a circuit C with s gates, the circuit C' has $O(s \log s)$ gates.

It is very natural to ask at this point whether this logarithmic overhead to construct a fault-tolerant circuit is best possible. Instead of using a simple repetition code, we might try to encode our computation using an error-correcting code with better parameters. In fact, it is well-known since Shannon's work¹⁸ that instead of encoding only one bit in m wires, we could encode a number of bits that is linear in m while keeping a comparable error probability. The first difficulty when using more complicated codes is the implementation of gates. This was particularly simple for the repetition code as described earlier: to implement a logical AND gate, it suffices to apply m AND physical gates between disjoint wires. Using the standard terminology used in quantum fault tolerance, we say that the repetition code has a transversal AND. The important property here is that the circuit to implement a logical and gates uses a physical circuit of constant depth and so errors cannot propagate too much. The second difficulty is to design an error reduction procedure using noisy gates for such general codes. In fact, it turns out that this logarithmic overhead is unavoidable as shown in Pippenger et al.¹⁷

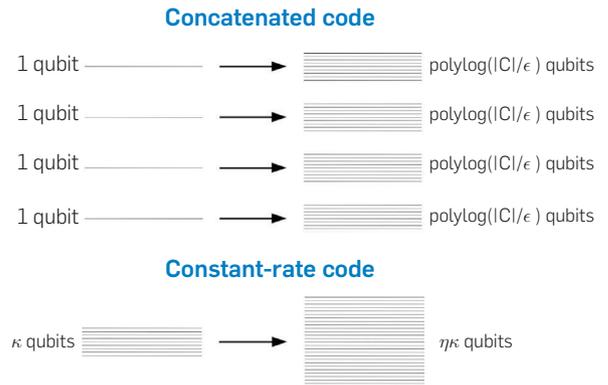
We finally note that for classical computers, fault tolerance is not needed in practice because with the development of the transistor, errors almost never occur.

1.2. Fault-tolerant quantum computation

On the other hand, for quantum computers, fault tolerance is really necessary. For this reason, immediately after Shor discovered his famous factoring quantum algorithm,¹⁹ the search for methods to reduce the effect of decoherence started. Shor himself showed that, perhaps contrary to what one could infer from the quantum no-cloning principle, quantum error-correcting codes do exist²⁰ and he made some steps toward fault tolerance.²¹ A few years later, the celebrated *threshold theorem* was proved. It states that upon encoding the logical qubits within the appropriate quantum error-correcting code, it is possible to transform an arbitrary quantum circuit C into a fault-tolerant one C' , such that even if the components of the circuit C' are subject to noise, below some threshold value it computes the same function as C .¹

Naturally, the fault-tolerant circuit C' will be larger than C . In particular, a number of additional qubits are required and the space overhead, that is, the ratio between the total number of qubits of the fault-tolerant circuit C' and the number of qubits of the ideal circuit C , scales polylogarithmically with the number of gates involved in the original computation. The depth and size overhead are also polylogarithmic, but we focus here on the space overhead. The polylogarithmic factor comes for a reason that is similar to the logarithmic factor in von Neumann's construction for the classical case. The main technique that is used to protect logical qubits is to use concatenated codes. In order to guarantee an overall failure probability ε for a circuit C

Figure 1. A natural idea to save on the memory overhead is to encode multiple qubits in the same block.



acting on κ qubits with $|C|$ locations,^a the fault-tolerant version of the circuits needs $O(\log \log (|C|/\varepsilon))$ levels of encoding, which translates into a $\text{polylog}(|C|/\varepsilon)$ space overhead (see Figure 1).

Although this might seem like a reasonably small overhead, this remains rather prohibitive in practice. As an example, an application of Shor's algorithm to factorize numbers of cryptographic interest would require a few thousand logical qubits, but tens of millions of physical qubits with the best fault-tolerant schemes currently available; see for example, Fowler et al.⁶ and Gidney and Ekerå.⁹ Given the extreme difficulty of controlling a large number of qubits, it is absolutely crucial to try to reduce the overhead of quantum fault tolerance as much as possible. From a computational point of view, it is also a very natural question to determine the optimal overhead required to achieve fault tolerance. As a classical computation is a special case of quantum computation, the previously mentioned logarithmic lower bound for fault-tolerant classical space overhead applies.¹⁷ However, in this context, it is natural to treat classical computations and quantum computations differently. In fact, it is very well motivated in practice to assume that classical computations are error-free but that quantum gates are noisy and to ask what is the minimal possible space overhead that can be achieved in this setting. In this model, building on Gottesman's framework,¹¹ we prove that quantum fault tolerance is possible with constant overhead (see Theorem 1). The main tool that we introduce here in order to achieve this goal is a class of quantum error correcting with good properties. These codes are called *quantum expander codes* and they are constant-rate low-density parity-check quantum codes with a decoding algorithm that can correct typical errors very efficiently even when the syndrome is noisy (see Theorem 3). Before introducing quantum expander codes, we give an overview

^a A location is any point in the circuit that could have an error, so it refers to a quantum gate, the preparation of a qubit in a given state, a qubit measurement, or a wait location if the qubit is not acted upon at a given time step.

of Gottesman's fault-tolerant scheme to motivate the desired properties of the quantum codes.

1.3. Gottesman's scheme

The natural approach to overcome the polylogarithmic barrier had been contemplated for a while, namely to rely on quantum error-correcting codes that encode multiple logical qubits within a block. Ideally, we would like to encode the κ logical qubits needed for the computation within a single quantum error-correcting code of length n with n linear in κ (see Figure 1) and then perform the gates corresponding to the computation within this code and regularly correcting (or more precisely reducing) the errors. However, turning this idea into a full-fledged scheme required much more work. The two main difficulties are to implement fault-tolerantly the logical gates and to correct the errors in a fault-tolerant way. In a breakthrough paper, Gottesman was able to overcome the first difficulty and partially the second one: he showed that polynomial-time computations could be performed with a noisy circuit with only a *constant* overhead provided that a family of quantum codes with good decoding properties was available.¹¹ In fact, this overhead can even be taken arbitrarily close to 1 provided that the physical error is sufficiently small.

We start by briefly describing how Gottesman's construction dealt with the difficulty of implementing the logical gates. One special gate that is used at the beginning of the computation is a preparation gate that prepares a fixed logical qubit state. We need to be able to apply this gate in a fault-tolerant way, that is, such that the number of qubits having an error is under control. In fact, using the technique of gate teleportation, once we are able to fault-tolerantly prepare a small number of fixed logical states, we can implement any logical gate in a fault-tolerant way. In order to achieve this fault-tolerant state preparation, Gottesman uses techniques based on code concatenation. But to keep the associated memory overhead small, we cannot prepare all the κ logical qubits in one shot. Instead, the κ logical qubits of the circuit C are partitioned into $\text{polylog}(\kappa)$ blocks of $\frac{\kappa}{\text{polylog}(\kappa)}$ qubits each and each block is encoded using a constant rate code. Then, the logical circuit C is "serialized" in such a way that a single gate is applied at each time step. In this way, at a given time step, only one gate is applied that acts on at most two logical qubits. Thus, at most two of the blocks are active and the overhead used for applying this gate is polylogarithmic in $\frac{\kappa}{\text{polylog}(\kappa)}$ and thus still linear in κ .

The error correction part of the fault-tolerant scheme is more relevant for the present work. The standard error correction procedure for a quantum error-correcting code is to perform a measurement that outputs a syndrome σ (this is in direct analogy with classical error-correcting codes) and then the decoding algorithm is a classical algorithm taking as input σ and returning an error E that is consistent with this syndrome. This error E is then undone by acting on the quantum systems. We refer to Section 2.2 for formal definitions of quantum error-correcting codes. If the quantum components used for this measurement are noisy, the obtained syndrome will in general be incorrect. One class of codes for which the number of errors in the syndrome stays

under control is low-density parity-check (LDPC) codes. This property is crucial as it ensures that the syndrome measurement circuit is of constant depth and thus errors cannot propagate too much.

Another property that the quantum code needs to have is that it can correct typical errors of size linear in the block-length n . This means that the minimum distance of the code should at least grow with n . And constant rate LDPC codes with minimum distance growing with n are quite difficult to construct. The situation is indeed much more involved than in the classical case where good LDPC codes (constant rate and linear minimum distance) can be found by picking a sparse parity-check matrix at random. In the quantum case, by contrast, the best known constructions display a minimum distance barely above the square-root of the length \sqrt{n} .⁷ But it is not sufficient to have quantum codes with large minimum distance: the decoding algorithm needs to be efficient. In fact, efficient decoding is crucial in the context of fault tolerance: while the decoding algorithm is running, the quantum circuit is waiting for the output of the decoding algorithm and thus errors keep accumulating. Thus, ideally, we would want the decoding to run in constant time that is independent of the number of qubits of the circuit. In addition to the efficiency, another important property that the decoding algorithm should have is that it should come with guarantees even if the observed syndrome σ is itself noisy. In fact, recall that the syndrome measurement circuit will be faulty and so its outcome will have a certain number of errors.

In the present work, we consider *quantum expander codes* introduced in Leverrier et al.¹⁵ obtained by taking the hypergraph product²⁴ of classical expander codes.²² We show that the SMALL-SET-FLIP decoding algorithm introduced in Leverrier et al.¹⁵ does satisfy all these properties. Namely, this algorithm can, in a constant number of time steps, reduce the size of a typical error by a constant fraction even if the observed syndrome is noisy.

We obtain the following general result by using our analysis of quantum expander codes in Gottesman's generic construction.¹¹

THEOREM 1. *For any $\eta > 1$ and $\varepsilon > 0$, there exists $p_\tau(\eta) > 0$ such that the following holds for sufficiently large κ . Let C be a quantum circuit acting on κ qubits, and consisting of $f(\kappa)$ locations for an arbitrary polynomial. There exists a circuit \tilde{C} using $\eta\kappa$ physical qubits, depth $\mathcal{O}(f(\kappa))$, and number of locations $\mathcal{O}(\kappa f(\kappa))$ that outputs a distribution, which has total variation distance at most ε from the output distribution of C , even if the components of C are noisy with an error rate $p < p_{th}$.*

2. QUANTUM EXPANDER CODES

In this section, we first review the construction of classical and quantum expander codes. We then discuss models of noise that are relevant in the context of quantum fault tolerance. We finally introduce the SMALL-SET-FLIP decoding algorithm for quantum expander codes.

2.1. Classical expander codes

A linear classical error-correcting code C of

dimension κ and length n is a subspace of \mathbb{F}_2^n of dimension κ . Mathematically, it can be defined as the κ -dimensional kernel of an $m \times n$ matrix H , called the parity-check matrix of the code: $C = \{x \in \mathbb{F}_2^n : Hx = 0\}$. The minimum distance d_{\min} of the code is the minimum Hamming weight of a nonzero code word: $d_{\min} = \min\{|x| : x \in C, x \neq 0\}$. Such a linear code is often denoted as $[n, \kappa, d_{\min}]$, and a code family has a *constant encoding rate* when $\kappa = \Theta(n)$. An important property for a linear code is the sparsity of H : the code is a *low-density parity-check* (LDPC) code when the rows and columns of H have a weight bounded by a constant.⁸ This is particularly attractive because it allows for efficient decoding algorithms, based on message passing for instance.

An alternative description of a linear code is *via* a bipartite graph known as its *factor graph* $G = (V \cup C, \mathcal{E})$ and defined as follows. The sets V of bits and C of check-nodes have cardinality n and m , respectively, and an edge is present between $v \in V$ and $c \in C$ whenever $H_{c,v} = 1$. In particular, any bipartite graph of constant maximum degree gives rise to an LDPC code. Depending on the description, an error is either a binary word $e \in \mathbb{F}_2^n$ or a subset $E \subseteq V$ whose indicator vector is e . Its corresponding *syndrome* is then either $\sigma(e) := He \in \mathbb{F}_2^m$ or the subset $\sigma(E) := \bigoplus_{v \in E} \Gamma(v) \subseteq C$ corresponding to the odd neighborhood of E in the graph. Here, $\Gamma(v) \subseteq C$ is the set of neighbors of v and the operator \oplus is interpreted as the symmetric difference of sets.

The codes that we will rely on for quantum fault tolerance are the quantum generalization of expander codes, which are the classical codes associated with *expander graphs*, and first considered by Sipser and Spielman.²²

DEFINITION 2 (EXPANDER GRAPH). *Let $G = (V \cup C, \mathcal{E})$ be a bipartite graph with left and right degrees bounded by d_v and d_c , respectively. We say that G is (γ, δ) -expanding if for any subset $S \subseteq A$ (with A is equal to either V or C) with $|S| \leq \gamma|A|$, we have $|\Gamma(S)| \geq (1 - \delta)d_A|S|$.*

Observe that we are requiring two-sided expansion for the graph. Even though only one-sided expansion is required for analyzing classical expander codes, the definition asks for two-sided expansion as this is used for the analysis of quantum expander codes. We note that the existence of (γ, δ) bipartite expanders can be shown via the probabilistic method provided that $d_A > \delta^{-1}$ and γ is a sufficiently small constant. Remarkably, classical expander codes come with an efficient decoding algorithm, *BIT-FLIP*, that can correct *arbitrary* errors of weight $\Omega(n)$, provided that $\delta < \frac{1}{4}$.²² The strategy behind the *BIT-FLIP* decoding algorithm is as simple as it can get: given some observed syndrome $\sigma(E)$, simply go through the bits $v \in V$ and flip any bit v if this decreases the syndrome weight, that is, if $|\sigma(E \oplus \{v\})| < |\sigma(E)|$. For a sufficiently expanding factor graph, and provided that the error weight is below γn , it is possible to show that there exist *critical bits* satisfying the condition above, and in fact, the number of such critical bits is linear in the size of E . Going through all the bits once will therefore decrease the syndrome weight by a constant fraction, and decoding will be achieved with logarithmic depth if the algorithm is suitably parallelized. In the context of fault tolerance, where

the syndrome is potentially noisy, the goal changes a little bit because it is not possible in general to correct all errors. In that case, it is sufficient to keep the error weight under control, and this can possibly be achieved by performing a constant number of rounds instead of a logarithmic one. Our present aim is to generalize these results to the quantum setting.

2.2. Quantum error-correcting codes

A quantum error-correcting code encoding κ logical qubits into n physical qubits is a subspace of $(\mathbb{C}^2)^{\otimes n}$ of dimension 2^κ . The *stabilizer* formalism developed by Gottesman¹⁰ allows one to describe a code as the kernel of a linear operator, exactly as in the classical case. A stabilizer group is an Abelian group $\langle g_1, \dots, g_m \rangle$ of n -qubit Pauli operators (n -fold tensor products of single-qubit Pauli operators $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$, $Y = ZX$, $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ and $I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$ with an overall phase of ± 1 or $\pm i$) that does not contain $-I$. The associated *stabilizer code* is defined as the common eigenspace of the generators g_1, \dots, g_m with eigenvalue ± 1 . If the generators are independent, then $\kappa = n - m$.

Devising good codes is significantly more complex in the quantum case because of the commutation requirement for the generators. A convenient way to enforce this condition is via the CSS construction,^{3, 23} where the stabilizer generators are either products of single-qubit X -Pauli matrices or products of Z -Pauli matrices. Commutativity should then only be verified between X -type generators (corresponding to products of Pauli X -operators) and Z -type generators, and this can be obtained directly by considering two classical linear codes C_x and C_z of length n with parity-check matrices H_x and H_z satisfying $H_x \cdot H_z^T = 0$. The generators of the stabilizer are of the form g_i^X , and g_i^Z is defined as

$$g_i^X = \bigotimes_{j: \text{s.t. } (H_z)_{ij}=1} X_j, \quad g_i^Z = \bigotimes_{j: \text{s.t. } (H_x)_{ij}=1} Z_j,$$

where X_j denotes the X Pauli operator applied to the j th factor, and where identity operators are omitted. The resulting quantum code has length n and encodes $\kappa = \dim C_x + \dim C_z - n$ logical qubits. Its minimum distance d_{\min} is defined in analogy with the classical case as the minimum Hamming weight of a Pauli operator mapping a code word to an orthogonal one. For the CSS code, one has $d_{\min} = \min(d_x, d_z)$ where $d_x = \min\{|E| : E \in C_x \setminus C_z^\perp\}$ and $d_z = \min\{|E| : E \in C_z \setminus C_x^\perp\}$, where the dual code C_x^\perp consists of words orthogonal to all words of C_x . Note that d_x can be larger than the minimum distance of the classical code C_x as we only consider the weight of code words in C_x that are not in C_z^\perp . In fact, for quantum LDPC codes, the minimum distance of the classical C_x will be bounded by a constant because the condition $H_x \cdot H_z^T = 0$ implies that the rows of H_z , which have a constant weight by the LDPC condition, are in C_x . As such, to construct interesting quantum LDPC codes, it is crucial to use the condition $E \notin C_z^\perp$. The reason the bistrings in C_z^\perp should not be considered as errors is that the corresponding X -type Pauli operators are in the stabilizer group and thus do not affect the state. Two Pauli X -type operators (e.g., errors) that are related by a Pauli X -type operator whose support is given by

an element in C_z^\perp are called *equivalent*. We say that $CSS(C_x, C_z)$ is a $[[n, \kappa, d_{\min}]]$ quantum code.

Even if the CSS framework simplifies matters a little bit, it remains nontrivial to find interesting codes subjected to the condition $H_x \cdot H_z^T = 0$. The hypergraph product code construction introduced by Tillich and Zémor gives a general method to turn a pair of *arbitrary* linear codes into a quantum CSS code.²⁴ In particular, starting with a classical code C with parity-check matrix H and a biregular (γ, δ) -expanding factor graph with vertex set $A \cup B$ (of size $n_A + n_B$) and left and right degrees d_A and d_B (satisfying $d_A \leq d_B$), one obtains a CSS code called *quantum expander code* with parity-check matrices H_x and H_z given by

$$H_x = (I_{n_A} \otimes H, H^T \otimes I_{n_B}),$$

$$H_z = (H \otimes I_{n_A}, I_{n_B} \otimes H^T).$$

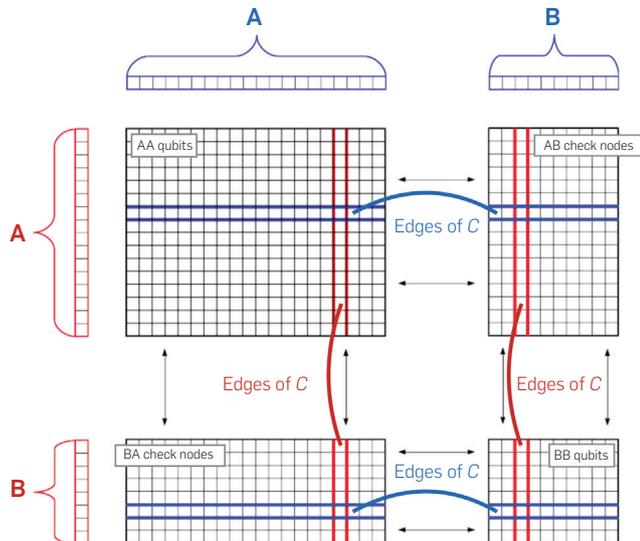
We illustrate this construction in Figure 2.

Quantum expander codes are LDPC with generators of weight $d_A + d_B$ and qubits involved in at most $2d_B$ generators, and they admit parameters $[[n, \kappa, d_{\min}]]$ with $\kappa = \Theta(n), d_{\min} = \Theta(\sqrt{n})$, provided that the expansion satisfies $\delta < \frac{1}{2}$.

2.3. Noise models

In the context of quantum fault tolerance, we are interested in modeling noise occurring during a quantum computation. In the circuit model of quantum computation, the effect of noise is to cause faults occurring at different locations of the circuit: on the initial state and ancillas, on gates (either active gates or storage gates) or on measurement gates. We refer to this model as *basic model* for fault tolerance. The main idea to perform a computation in a fault-tolerant manner is then to encode the logical qubits with a quantum

Figure 2. An illustration of quantum expander codes. Starting with a bipartite expander graph between the vertex sets A and B , the quantum expander code is defined by two bipartite graphs: H_x between the set of qubit nodes $(A \times A) \cup (B \times B)$ and the check nodes $A \times B$ and H_z between the qubit nodes $(A \times A) \cup (B \times B)$ and the check nodes $B \times A$.



error-correcting code, replace the locations of the original circuit by gadgets applying the corresponding gate on the encoded qubits, and interleave the steps of the computation with error correction steps. In general, it is convenient to abstract away the details of the implementation and consider a *simplified model* of fault tolerance where one is concerned with only two types of errors: errors occurring at each time step on the physical qubits, and errors on the results of the syndrome measurement. The link between the basic and the simplified models for fault tolerance can be made once a specific choice of gate set and gadgets for each gate is made. This is done for instance in Section 7 of Gottesman.¹¹ In other words, the simplified model of fault tolerance allows us to work with quantum error-correcting codes where both the physical qubits and the check nodes are affected by errors.

As usual in the context of quantum error correction, we restrict our attention to Pauli-type errors acting on the set V of qubits because the ability to correct all Pauli errors of weight t implies that arbitrary errors of weight t can be corrected. In particular, one only needs to address X - and Z -type errors because a Y -error corresponds to simultaneous X - and Z -errors. Therefore, we think of an error pattern on the qubits as a pair (E_x, E_z) of subsets of the set of qubits V . This should be interpreted as Pauli error X on all qubits in $E_x \setminus E_z$, error Y on $E_x \cap E_z$ and error Z on $E_z \setminus E_x$. In the case of a CSS code, the syndrome associated to this error pattern should be $(\sigma_x(E_x), \sigma_z(E_z))$ but errors will also affect the syndrome extraction, leading to an observed syndrome (σ_x, σ_z) given by

$$\sigma_x := \sigma_x(E_x) \oplus D_x, \quad \sigma_z := \sigma_z(E_z) \oplus D_z,$$

where the error on the syndrome consists of two classical strings (D_x, D_z) , which are subsets of the sets C_x and C_z of check nodes, whose values have been flipped.

How to properly model the effect of noise in a quantum computer is a delicate question. In particular, the assumption of independence of errors affecting distinct qubits is not well justified because the topology of the quantum circuit will generally create correlations between errors. For this reason, a particular reasonable approach suggested by Gottesman consists in only making the assumption that the probability of an error decays exponentially with its weight.¹¹ The relevant error model for the pair (E_x, D_x) is the *local stochastic noise model* with parameters (p, q) defined by requiring that for any $F \subseteq V$ and $G \subseteq C_x$, the probability that F and G are part of the qubit and syndrome errors, respectively, is bounded as follows:

$$\mathbb{P}[F \subseteq E_x, G \subseteq D_x] \leq p^{|F|} q^{|G|}.$$

The error model is exactly the same for the pair (E_z, D_z) . Note that, as the decoding algorithm we use does not take into account correlations between X and Z errors, the joint distribution between (E_x, D_x) and (E_z, D_z) will not affect the analysis.

2.4. The SMALL-SET-FLIP decoding algorithm

If the syndrome extraction is noiseless, a decoder is given the pair (σ_x, σ_z) of syndromes and should return a pair of

errors (\hat{E}_X, \hat{E}_Z) such that $E_X \oplus \hat{E}_X \in \mathcal{C}_Z^\perp$ and $E_Z \oplus \hat{E}_Z \in \mathcal{C}_X^\perp$. In that case, the decoder outputs an error equivalent to (E_X, E_Z) , and we say that it succeeds.

A natural approach to perform error correction (in the noiseless syndrome case) would be to directly mimic the classical BIT-FLIP decoding algorithm analyzed by Sipser and Spielman, that is try to apply X -type (or Z -type) correction to qubits when it leads to a decrease of the syndrome weight. Unfortunately, in that case, there are error configurations of constant weight that cannot be corrected in this way. This led Leverrier et al.¹⁵ to introduce the SMALL-SET-FLIP strategy that we describe next.

Focusing on X -type errors for instance, and assuming that the syndrome $\sigma = \sigma_X(E)$ is known, the algorithm cycles through all the X -type generators of the stabilizer group (i.e., the rows of H_Z), and for each one of them, it determines whether there is an error pattern contained in the generator that decreases the syndrome weight. Assuming that this is the case, the algorithm applies the error pattern (choosing the one maximizing the ratio between the syndrome weight decrease and the pattern weight, if there are several). The algorithm then proceeds by examining the next generator. Because the generators have constant weight $d_A + d_B$, there are $2^{d_A + d_B} = \mathcal{O}(1)$ possible patterns to examine for each generator.

Before describing the algorithm more precisely, let us introduce some additional notations. Let \mathcal{X} be the set of subsets of V corresponding to X -type generators: $\mathcal{X} = \{\text{Supp}(g_i^X) : i \in [m]\} \subseteq \mathcal{P}(V)$, where $\mathcal{P}(V)$ is the power set of V . Here, m denotes the number of X -type generators, and $\text{Supp}(g_i^X)$ denotes the subset of qubits on which g_i^X acts nontrivially. The indicator vectors of the elements of \mathcal{X} span the dual code \mathcal{C}_Z^\perp . The condition for successful decoding of the X -type error E is that E equivalent to the output of the decoding algorithm \hat{E} , i.e., there exists a subset $X \subset \mathcal{X}$ such that $E \oplus \hat{E} = \bigoplus_{x \in X} x$. At each step, the SMALL-SET-FLIP algorithm tries to flip a subset of $\text{Supp}(g_i^X)$ for some generator g_i^X , which decreases the syndrome weight $|\sigma|$. In other words, it tries to flip some element $F \in \mathcal{F}_0$ such that $\Delta(\sigma, F) > 0$ where:

$$\begin{aligned} \mathcal{F}_0 &:= \{F \subseteq g_i^X : i \in [m]\}, \\ \Delta(\sigma, F) &:= |\sigma| - |\sigma \oplus \sigma_X(F)|. \end{aligned} \quad (1)$$

The SMALL-SET-FLIP decoding algorithm consists of two iterations of Algorithm 1 below: it first tries to correct X -type errors by examining the corresponding syndrome $\sigma_X(E_X)$, and then, it is applied a second time (exchanging the roles of X and Z) to correct Z -type errors. The idea of applying the same decoder twice, to correct first X -type errors, and then Z -type errors, is particularly natural when considering a CSS code. Note that this is a suboptimal strategy in general because both types of errors could be correlated, but this will be sufficient for our purpose and this significantly simplifies the exposition.

Algorithm 1: SMALL-SET-FLIP for noiseless syndrome.

INPUT: a syndrome $\sigma = \sigma_X(E) \subseteq C_X$, corresponding to an unknown X -type error pattern $E \subseteq V$

OUTPUT: $\hat{E} \subseteq V$, a guess for the error pattern

SUCCESS: if $E \oplus \hat{E} = \bigoplus_{x \in X} x$ for $X \subseteq \mathcal{X}$, i.e., E and \hat{E} are equivalent errors

```

 $\hat{E}_0 = 0; \sigma_0 = \sigma; i = 0$ 
while  $(\exists F \in \mathcal{F}_0 : \Delta(\sigma_i, F) > 0)$  do
     $F_i = \arg \max_{F \in \mathcal{F}_0} \frac{\Delta(\sigma_i, F)}{|F|}$ 
     $\hat{E}_{i+1} = \hat{E}_i \oplus F_i$ 
     $\sigma_{i+1} = \sigma_i \oplus \sigma_X(F_i)$  //  $\sigma_{i+1} = \sigma_X(E \oplus \hat{E}_{i+1})$ 
     $i = i + 1$ 
end while
return  $\hat{E}_i$ 

```

Leverrier et al.¹⁵ studied the decoding algorithm SMALL-SET-FLIP and showed that it corrects arbitrary *qubit* errors of size $\mathcal{O}(\sqrt{n})$ for quantum expander codes (when the syndrome extraction is noiseless) provided that the expansion of the graph satisfies $\delta < \frac{1}{6}$.

This analysis was extended to the case of random errors (either independent and identically distributed, or local stochastic) provided that the syndrome extraction is performed perfectly and under a stricter condition on the expansion of the graph.⁵ More precisely, for quantum expander codes with an expansion $\delta < \frac{1}{8}$, there exist a probability $p_0 > 0$ and constants C, C' such that if the noise parameter on the qubits satisfies $p < p_0$, the SMALL-SET-FLIP decoding algorithm described above runs in time linear in the code length and corrects a random error with probability at least $1 - Cn(\frac{p}{p_0})^{C'\sqrt{n}}$.

The analysis of the decoding algorithm is inspired by the work of Kovalev and Pryadko¹⁴ who studied the behavior of the maximum likelihood decoding algorithm (that has exponential running time in general). We represent the set of qubits as a graph $\mathcal{G} = (V, \mathcal{E})$ called *adjacency graph* where the vertices correspond to the qubits of the code and two qubits are linked by an edge if there is a stabilizer generator that acts on the two qubits. The approach is then to show that provided the vertices E corresponding to the error do not form large *connected* subsets, the error can be corrected by the decoding algorithm. How large the connected subsets are allowed to be is related to the minimum distance of the code for the maximum-likelihood decoder or to the maximum size of correctable errors for more general decoders. This naturally leads to studying the size of the largest connected subset of a randomly chosen set of vertices of a graph. This is also called site percolation on finite graphs and is a well-studied topic.

In order to analyze the efficient SMALL-SET-FLIP decoding algorithm for quantum expander codes, a slightly more complex notion of connectivity turns out to be relevant. Namely, instead of studying the size of the largest connected subset of E , one studies the size of the largest connected α -subset of E . We say that X is an α -subset of E if $|X \cap E| \geq \alpha|X|$. Note that for $\alpha = 1$, this is the same as X is a subset of E . Then, one shows that, if the probability of error of each qubit is below some threshold depending on α and the degree of \mathcal{G} , then the probability that a random set E has a connected α -subset of size $\Omega(\sqrt{n})$ vanishes as $e^{-\Omega(\sqrt{n})}$. As SMALL-SET-FLIP can correct errors of size $\mathcal{O}(\sqrt{n})$, one concludes that random errors of linear size are corrected with high probability. The

key property of SMALL-SET-FLIP that is used here is its “locality”: at each step, errors on distant qubits are decoded independently. We refer the reader to Fawzi et al.⁵ for the details of the analysis.

3. DECODING WITH A NOISY SYNDROME

In the quantum fault tolerance setting, the syndrome extraction cannot be assumed to be noiseless anymore, and we must consider that the decoding algorithm is fed with noisy syndromes of the form

$$\sigma_x := \sigma_x(E_x) \oplus D_x, \quad \sigma_z := \sigma_z(E_z) \oplus D_z, \quad (2)$$

described by a local stochastic noise model of parameters p and q . As before, we focus on correcting X -type errors so we write E for E_x and D for D_x .

In the case where $D = \emptyset$, we saw in the previous section that the SMALL-SET-FLIP decoding algorithm succeeds in outputting \hat{E} that is equivalent to E provided E is local stochastic with a sufficiently small parameter. In the noisy case $D \neq \emptyset$, the success condition for the decoding algorithm is different. We cannot hope to entirely correct the error because any single qubit error cannot be distinguished from a well-chosen constant weight syndrome bit error. Perhaps surprisingly, we will be using the same SMALL-SET-FLIP decoding algorithm for this noisy case: we keep flipping sets F that decrease the syndrome weight until we cannot do so anymore. In this case, we end up with a final syndrome that is in general not empty, but instead, we prove in Theorem 3 that when $\delta < \frac{1}{16}$, the correction provided by the SMALL-SET-FLIP algorithm leads to a residual error that is local stochastic with controlled parameters.

Before stating the theorem, we note that the fact that we use the same decoding algorithm even with a noisy syndrome is a remarkable feature of SMALL-SET-FLIP for quantum expander codes. In fact, for many other codes such as surface codes, it is necessary not only to change the decoding algorithm but also to repeat the syndrome measurement several times and to apply a more complicated decoding algorithm that depends on all of these outcomes. This property of the SMALL-SET-FLIP algorithm is called *single-shot* in the fault-tolerant quantum computation literature.²

THEOREM 3 (INFORMAL). *There exist constants $p_0 > 0, p_1 > 0$ such that the following holds. Consider a bipartite graph with sufficiently good expansion and the corresponding quantum expander code. Consider random errors (E, D) satisfying a local stochastic noise model with parameter $(p_{\text{phys}}, p_{\text{synd}})$ with $p_{\text{phys}} < p_0$ and $p_{\text{synd}} < p_1$. Let \hat{E} be the output of the SMALL-SET-FLIP decoding algorithm on the observed syndrome. Then, except for a failure probability of $e^{-\Omega(\sqrt{n})}$, the remaining error $E \oplus \hat{E}$ is equivalent to E_{ls} that has a local stochastic distribution with parameter $p_{\text{synd}}^{\Omega(1)}$.*

In the special case where the syndrome measurements are perfect, that is, $p_{\text{synd}} = 0$, the statement guarantees that for a typical error of size at most $p_0 n$, the SMALL-SET-FLIP algorithm finds an error that is equivalent to the error that occurred. If the syndrome measurements are noisy, then

we cannot hope to recover an equivalent error exactly, but instead we can control the size of the remaining error $E \oplus \hat{E}$ by the amount of noise in the syndrome measurements. In particular, for any qubit error rate below p_0 , the decoding operation reduces this error rate to be $p_{\text{synd}}^{\Omega(1)}$ (our choice of p_0 will be such that $p_{\text{synd}}^{\Omega(1)} \ll p_0$). This criterion is sufficient for fault-tolerant schemes as it ensures that the size of the qubit errors stay bounded throughout the execution of the circuit. The proof of this theorem consists of two main parts: analyzing arbitrary errors of weight $\mathcal{O}(\sqrt{n})$ and then exploiting percolation theory to analyze stochastic errors of linear weight.

3.1. Sketch of the analysis

The SMALL-SET-FLIP decoding algorithm proceeds by trying to flip small sets of qubits so as to decrease the weight of the syndrome, and the main challenge in its analysis is to prove the existence of such a small set F . In the case where the observed syndrome is error free, Leverrier et al.¹⁵ and Fawzi et al.⁵ relied on the existence of a “critical generator” to exhibit such a set of qubits. This approach, however, only yields a *single* such set F , and when the syndrome becomes noisy, nothing guarantees anymore that flipping the qubits in F will result in a decrease of the syndrome weight and it becomes unclear whether the decoding algorithm can continue. Instead, in order to take into account the errors on the syndrome measurements, we would like to show that there are *many* possible sets of qubits F that decrease the syndrome weight. In order to establish this point, we consider an error E of size below the minimum distance and we imagine running the SMALL-SET-FLIP decoding algorithm *without errors on the syndrome*. The algorithm gives a sequence of small sets $\{F_i\}$ to flip successively in order to correct the error. In other words, we obtain the following decomposition of the error, $E = \bigoplus_i F_i$ (note that the sets F_i might overlap). The expansion properties of the graph guarantee that there are very few intersections between the syndromes $\sigma(F_i)$. This ensures that a linear number of these F_i 's can be flipped to decrease the syndrome weight at the current step. More formally, one can prove the following statement.

PROPOSITION 4. *There exist constants c_1, c_2, γ_0 such that the following statement holds. Suppose the current error E satisfies $|E| \leq \gamma_0 \sqrt{n}$ and let $\tilde{\sigma} = \sigma_x(E) \oplus D$, then there exists $\mathcal{F}^* \subseteq \mathcal{F}_0$ such that:*

1. $\Delta(\tilde{\sigma}, F) \geq (\frac{1}{2} - 8\delta) |\sigma_x(F)|$ for all $F \in \mathcal{F}^*$,
2. $\sum_{F \in \mathcal{F}^*} |\sigma_x(F)| \geq c_1 |\sigma_x(E)| - c_2 |D|$.

With this, provided that the syndrome of the current error is still large compared to the number of errors D on the syndrome, there will remain some $F \in \mathcal{F}^*$ that can be flipped in order to decrease the syndrome weight and the SMALL-SET-FLIP algorithm can continue. This guarantees then when running the algorithm, the size of the residual error $E \oplus \hat{E}$ can be upper bounded by $c|D|$, for some constant c .

In order to analyze random errors of linear weight, we use percolation theory for α -connected sets similar to the

noiseless syndrome case described in the previous section. The main difference is that we use the *syndrome adjacency graph* of the code, which is similar to the adjacency graph except that we also include check nodes as vertices. This is in order to ensure the “locality” of the decoding algorithm with respect to this graph, implying that each cluster of the error is corrected independently of the other ones. Using the fact that clusters are of size bounded by $\mathcal{O}(\sqrt{n})$, the result on low weight errors shows that the size of $E \oplus \hat{E}$ is controlled by the syndrome error size. In order to show that the error after correction is local stochastic, a more delicate analysis is needed. For this, we introduce the notion of witness to assign residual qubit errors to neighboring syndrome errors. We refer to Fawzi et al.⁴ for details.

3.2. Parallelizing SMALL-SET-FLIP

We established that at each step of Algorithm 2.4, there are many possible flips F that decrease the syndrome weight. We already exploited this property to handle a noisy syndrome, but it can also be used to parallelize the decoding algorithm. In fact, we can now flip several of these small sets F *simultaneously*. However, we have to pay attention to the fact that the sets $\sigma_X(F)$ could intersect. In order to avoid that, we introduce a coloring of the X -type generators: if g_1 and g_2 have the same color, then for any $F_1 \subseteq \Gamma_X(g_1)$ and $F_2 \subseteq \Gamma_X(g_2)$: $\sigma_X(F_1) \cap \sigma_X(F_2) = \emptyset$. It is simple to show that the set C_Z of all the X -type generators can be partitioned using a constant number χ of color classes $C_Z = \cup_{k=1}^{\chi} C_Z^k$.

This leads to Algorithm 2 that is a parallelized version of Algorithm 1 where we flip all the small sets that decrease the syndrome weight sufficiently and that have the same color. Let us discuss the stopping condition for this parallelized decoding algorithm. The natural stopping condition (which is not exactly the one used in Algorithm 2) here would be similar to the sequential version: when no more flips decrease the syndrome weight. As one can show that the syndrome weight decreases by a constant fraction at each step, the number of steps for this algorithm would be of order and $\mathcal{O}(\log n)$ we obtain the same result as in Theorem 3: the residual error is local stochastic with parameter only depending on p_{synd} and not on the size of the initial error. Instead, in Algorithm 2, we apply a fixed number of steps f_0 , where f_0 is a well-chosen constant that depends on the degrees and expansion parameters of the expander graph. This allows the decoding algorithm to run in constant time, which is important for fault tolerance if we do not assume that classical computations are instantaneous. But the price to pay is that the residual error will not only depend on syndrome error rate p_{synd} but also on the qubit error rate p_{phys} . In particular, even if the syndrome was perfect, this algorithm would only reduce the size of the error but not completely correct it. This is however good enough in the context of fault tolerance. We refer the reader to Grospellier¹² for more details.

Algorithm 2: Parallel SMALL-SET-FLIP decoding algorithm.

INPUT: $\tilde{\sigma} \subseteq C_X$ a syndrome where $\tilde{\sigma} = \sigma_X(E) \oplus D$ with $E \subseteq V$ an error on qubits and $D \subseteq C_X$ an error on the syndrome

OUTPUT: $\hat{E} \subseteq V$, a guess for the error pattern

```

 $\hat{E}_0 = \emptyset$ ;  $\tilde{\sigma}_0 = \tilde{\sigma}$ 
for  $i \in \llbracket 0; f_0 - 1 \rrbracket$  do //  $f_0$  is a parameter
   $\kappa = i \bmod \chi$  // current color
  in parallel for  $g \in C_Z^\kappa$  do
    if  $\exists F \subseteq \Gamma_Z(g), \Delta(\tilde{\sigma}_i, F) \geq (\frac{1}{2} - 8\delta) |\sigma_X(F)|$  then
       $F_g =$  arbitrary such  $F$ 
    else
       $F_g = \emptyset$ 
    end if
  end parallel for
   $F_i = \bigoplus_{g \in C_Z^\kappa} F_g$ 
   $\hat{E}_{i+1} = \hat{E}_i \oplus F_i$ 
   $\tilde{\sigma}_{i+1} = \tilde{\sigma}_i \oplus \sigma_X(F_i)$  //  $\tilde{\sigma}_{i+1} = \sigma_X(E \oplus \hat{E}_{i+1}) \oplus D$ 
end for
return  $\hat{E}_i$ 

```

THEOREM 5. *There exist constants $p_0 > 0, p_1 > 0$ such that the following holds. Suppose the pair (E, D) satisfies a local stochastic noise model with parameter $(p_{\text{phys}}, p_{\text{synd}})$ where $p_{\text{phys}} < p_0$ and $p_{\text{synd}} < p_1$. Then, there exists an event succ that has probability $1 - e^{-\Omega(\sqrt{n})}$ and a random variable E_{ls} that is equivalent to $E \oplus \hat{E}$ such that conditioned on $\text{succ}, E_{\text{ls}}$ has a local stochastic distribution with parameter $p_{\text{ls}} = p_0^2$.*

Note that there is nothing special about the square in the expression p_0^2 , and this can be replaced by p_0^c for any $c > 1$. When c increases, the local stochastic parameter p_{ls} of the remaining error gets better but at the cost of a larger number of steps, f_0 .

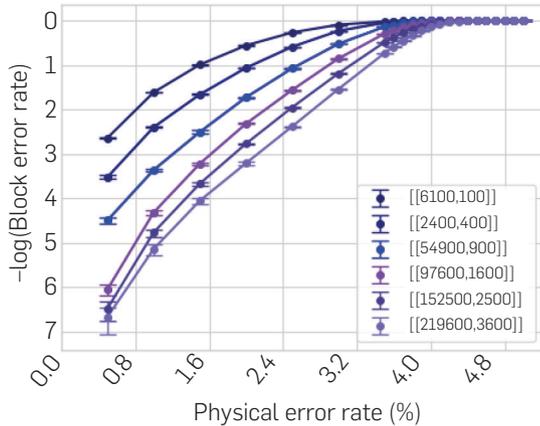
4. CONCLUSION

In this work, we have designed a very efficient decoding algorithm for quantum expander codes that has multiple good properties that are particularly suited for fault-tolerant quantum computation with a small memory overhead. This work should be seen as a theoretical proof of principle and we now mention some limitations of this work and avenues for future research.

A first limitation is that the statements we obtain here are asymptotic in the limit of very large computation. In particular, even though the value of the threshold (i.e., the tolerated error rate) we obtain is a constant, its value is extremely small to be of practical use: an estimate gives 10^{-58} . Part of the explanation is due to the very crude bounds that we obtain via percolation theory arguments. In this work, we have not tried to optimize the value of the threshold and have instead tried to simplify the general scheme as much as possible. As shown in Figure 3, numerical simulations¹³ suggest nevertheless that the threshold value for expander codes could be comparable to the best constructions based on concatenating surface codes.

Another limitation is in the geometry of quantum expander codes. Measuring the syndrome is simple in the sense that one needs to act on a small number of qubits, but the qubits will in general not be *geometrically* local. Performing gates that are not geometrically local may be significantly harder than nearest neighbor gates for many

Figure 3. Logical error rates after decoding quantum hypergraph product codes of various blocklengths with the SMALL-SET-FLIP algorithm, as a function of the physical error rate for i.i.d. X-Pauli errors. These simulations were done with perfect syndrome (figure from Grouès et al.¹³).



quantum computing architectures. Note that this is in contrast to the surface code for which the syndrome bits can be obtained by performing an operation on four neighboring qubits on a two-dimensional lattice. One interesting (architecture-dependent) question for future research is to quantify to which extent a gain in the encoding rate justifies the additional difficulty to perform gates that are not geometrically local.

A third limitation is that for our analysis to apply, we need bipartite expander graphs with a large (vertex) expansion. One issue is that there is no known efficient algorithm that can deterministically construct such graphs. Although algorithms to construct graphs with large *spectral* expansion are known, they do not imply a sufficient vertex expansion for our purpose. Random graphs will display the right expansion (provided their degree is large enough) with high probability, and it is not known how to check efficiently that a given graph is indeed sufficiently expanding.

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