

Local fault-tolerant quantum computation

Krysta M. Svore,^{1,*} Barbara M. Terhal,^{2,†} and David P. DiVincenzo^{2,‡}

¹*Columbia University, 1214 Amsterdam Avenue, MC:0401, New York, New York 10025, USA*

²*IBM Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598, USA*

(Received 15 October 2004; revised manuscript received 16 March 2005; published 16 August 2005)

We analyze and study the effects of locality on the fault-tolerance threshold for quantum computation. We analytically estimate how the threshold will depend on a scale parameter r which characterizes the scale-up in the size of the circuit due to encoding. We carry out a detailed seminumerical threshold analysis for concatenated coding using the seven-qubit CSS code in the local and the ‘nonlocal’ setting. First, we find that the threshold in the local model for the $[[7,1,3]]$ code has a $1/r$ dependence, which is in correspondence with our analytical estimate. Second, the threshold, beyond the $1/r$ dependence, does not depend too strongly on the noise levels for transporting qubits. Beyond these results, we find that it is important to look at more than one level of concatenation in order to estimate the threshold and that it may be beneficial in certain places, like in the transportation of qubits, to do error correction only infrequently.

DOI: [10.1103/PhysRevA.72.022317](https://doi.org/10.1103/PhysRevA.72.022317)

PACS number(s): 03.67.Lx, 03.67.Pp

I. INTRODUCTION

The issue of fault tolerance is central to the future of quantum computation. Most studies of fault tolerance until now [1–4] have focused on deriving fault tolerance in a setting where gates between any two qubits can be executed instantaneously, i.e., without taking into account the potential necessity to move qubits close together in space prior to gate execution. We call this setting the nonlocal model. Current estimates of the fault-tolerance threshold in the probabilistic independent nonlocal error model can be found in the extensive studies performed by Steane [5], estimating the threshold failure probability as $O(10^{-3})$. The recent results by Knill [6] and Reichardt [7] even give estimates that can be an order of magnitude better, i.e., $O(10^{-2})$.

It has been argued (see [1,5,8] and the analysis in [9]) that the local model, where qubit transportation is required, would still allow for a fault-tolerance threshold, albeit somewhat lower than in the nonlocal model. However, there has not been any assessment of how exactly locality influences the threshold, i.e., what is the dependence on the code, the spatial size of the error-correction procedure, the failure rates on the qubit wires, etc. Such an assessment is timely, because the post-selected schemes by Knill [6] in which large entangled states are prepared in a trial-and-error fashion (and to a smaller certain extent also the ancilla preparation procedure proposed by Reichardt [7]) may fare worse compared to the more ‘conventional’ methods of computation and error correction when locality is taken into account. This is because the method of postselection is based on attempting to create many states in parallel, of which a few may pass the test and are integrated in the computation. If the success probability is low, then at no additional cost in the nonlocal model, one can increase the number of parallel tries of creating these

states. In the local model, however, it must be taken into account that an increase in the number of parallel tries increases the amount of qubit movement, and thus the potential for errors.

In the first part of this paper, we make a purely analytical estimate of the threshold when locality is taken into account and show its dependence on a scale factor r , which is a measure of the spatial scale-up that is due to coding. This estimate can be applied to all known error models for which a fault-tolerance threshold result currently exists.

Since this estimate may be very rough, we set out in the second part of this paper to analyze and compare, using the ‘conventional’ method of error correction as described by Steane in [5], the fault-tolerant behavior for the concatenated seven-qubit CSS $[[7,1,3]]$ code for the local and nonlocal model.

In our analysis, we focus on concatenated coding and the threshold result. This is not to say that the strategy of using a large code once so that logical failure rates are small enough for the type of computation that we envision (see [10]) may not be of equal or greater practical interest. In such a scenario, one ‘merely’ has to optimize the error-correction procedures and encoded gate operations for locality.

Here are some of our semianalytical findings for the seven-qubit code. In these studies, we have used the nonlocal error-correction routine and have looked at the effects of the noise level during transportation of qubits and the scale-up of the computation due to coding.

(i) In the entirely nonlocal setting, we find that one really needs to look at higher levels of concatenation to estimate a correct threshold. For the model where all gates have the same failure probability γ_{else} and memory errors are one-tenth of the gate failure probabilities $\gamma_w = \gamma_{else}/10$, we find a threshold value of $\gamma_{else} = 3.4 \times 10^{-4}$. This is smaller than what Steane estimates in Ref. [5].

(ii) We find that, in the local setting, the threshold scales as $\Theta(1/r)$. For example, for $r=20$ and for the failure of movement over a unit distance equal to the failure probability γ_{else} , and for memory errors equal to one-tenth of γ_{else} ,

*Electronic address: kmsvore@cs.columbia.edu

†Electronic address: terhal@watson.ibm.com

‡Electronic address: divince@watson.ibm.com

we find that the threshold value for γ_{else} is 7.3×10^{-5} .

(iii) We find that the threshold does not depend very strongly on the noise levels during transportation.

(iv) We find that infrequent error correction may have some benefits while qubits are in the “transportation channel.”

II. A LOCAL ARCHITECTURE

Let us first discuss the existence of a fault-tolerance threshold in the local model of quantum computation. It is clear that for unencoded computations, at most a linear (in the number of qubits) overhead is incurred in order to make gates act on nearest-neighbor qubits.

If we perform concatenated coding in order to decrease the logical failure rate, we note that the circuit grows in size exponentially in the level of concatenation. Therefore, the distances over which qubits have to be transported (see [18]) and thus the number of places in time and space where errors can occur will increase. This will inevitably increase the logical failure rate at the next level of concatenation as compared to the logical failure rate in the nonlocal model. In order to be below the noise threshold, we want the logical failure rate to decrease at higher levels of concatenation. Thus it becomes a question of whether the extra increase in logical failure rate due to locality is sufficiently bounded so that there is still a noise value below which the logical failure rate decreases at the next level of concatenation. The question has been answered positively in the literature, see [1,9]. In particular, in Ref. [9], two simple, significant observations were made which are important in deriving the existence of a threshold in local fault-tolerant computation.

(i) The most frequent operations during the computation should be the most local operations. For concatenated computation, the most frequent operation is lowest-level error correction. Thus the ancillas needed for this error correction should be adjacent to the qubits that are being corrected. The next most frequent is level 1 error correction, and so on. In Fig. 1, an example of a layout following these guidelines is given (see also [9] itself).

(ii) The circuitry that replaces the nonlocal circuitry, say an error-correction routine or an encoded gate operation, should be made according to the rules of fault tolerance. For example, it is undesirable to swap a data qubit with another data qubit in the same block, since a failure in the swap gate will immediately produce two data errors. Local swapping could potentially be done with dummy qubits, whose state is irrelevant for the computation.

The third observation, which is less explicitly stated in Ref. [9], is based on the following. Let us assume that we follow the requirement for hierarchically putting error-correction ancillas near the data. We first start by making the original circuit a circuit with only nearest-neighbor gates according to the specific architecture. We call this circuit M_0 and concatenate once to obtain circuit M_1 , twice to obtain circuit M_2 , etc. In circuit M_1 , we have replaced qubits from M_0 by encoded qubits and their ancilla qubits for error correction (or local gate operations). Thus every qubit becomes a “blob” of qubits with a certain spatial size. In order to do a

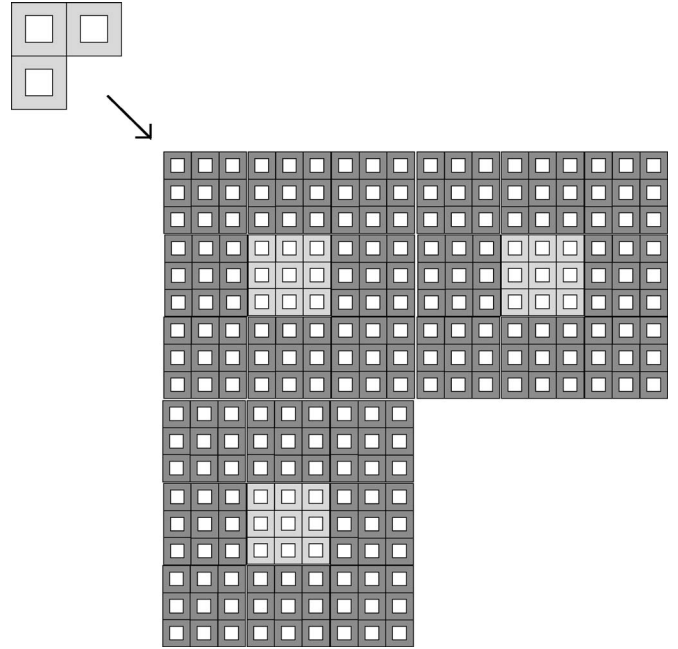


FIG. 1. Two-dimensional plane with the spatial layout of M_1 and M_2 . The grayness of the area indicates the amount of moving the qubits potentially need to do.

two-qubit gate g from M_0 , we have to move the data qubits in this blob past or over these ancillary qubits in order to interact with other data qubits (see [19]). Let us say that the scale of the blob is given by a parameter r so that in order to do the encoded two-qubit gate, the qubits have to be moved over a distance r . At the next level of concatenation, again every qubit “point” becomes a blob, which implies that in order to do the doubly encoded version of $g \in M_0$, a doubly encoded block has to move over distance r^2 . The two-qubit gates in the error correction of M_1 involving the level 1 error-correcting ancillas have to be moved over a distance r , and the level 0 error-correcting ancillas, which are added in M_2 , are “local,” assuming that we made the error-correction routine itself local. Thus in general, in M_n , level k ancillas, $k=0, \dots, n-1$, may have to be moved over a distance which scales as r^k , exponential in the number of levels of concatenation.

Let us assume that the failure probability of a traveling qubit is approximately linear in distance d , i.e., $p_{err} = 1 - (1-p)^d \approx dp$, where p is the failure probability per unit distance. For many implementations, the distances involved in moving level k ancillas, as well as the failure rates, will be far too large and error correction will have to be done frequently while the qubits are in transit. In fact, a threshold will probably not even exist if there is no error correction done in transit. This is because at some level of concatenation the failure rates for the high-level ancillas are such that these ancillas completely decohere in transit. At that point, any additional level of concatenation can only make things worse, not better. In Sec. III, we give the details of a model where (lower-level) error correction on “moving qubits” is included in the concatenation steps.

If we think about realistic architectures for any type of physical implementation, it is likely that the stationary qubits

lie in a one-dimensional, two-dimensional, or a few stacks of two-dimensional planes, potentially clustered in smaller groups. The reason is that one likely needs the third dimension for the classical controls that act on the qubits as in ordinary computation.

Given the discussion above, we can imagine a two-dimensional layout of qubits as in Fig. 1. In M_1 , every block of data qubits surrounds stationary level 0 ancillas, indicated by the white area. The data qubits themselves have to be moved (over distance r) either out of the plane, or by “wires” in the plane, in order to interact with the nearest-neighbor block of data qubits. In M_2 , we again have the stationary “white” level 0 ancillas, light gray areas for level 1 ancillas that now have to be moved over distance r , and the dark gray areas for data qubits which potentially have to be moved over distance r^2 .

In this paper, we do not go into details about the mechanisms behind qubit movement. Inside the error-correction procedure, depending on the implementation, one may think about swapping qubits or creating short-ranged EPR pairs in order to teleport qubits. For the longer distances, one may create a grid of EPR pairs, using quantum repeater techniques [11], which is maintained by frequent entanglement distillation, or alternatively convert stationary qubits into more mobile forms of qubits (photons, spin waves, etc.). In Sec. III, we lay out a model for error correction “along the way,” but we do not discuss how or where in space this additional error correction can take place. This could be the subject of future research.

III. LOCAL FAULT TOLERANCE: AN ANALYTIC LOWER BOUND

We follow the derivation of fault-tolerant quantum computation as in Ref. [12], which has also been used in [4] to deal with more general error models such as non-Markovian noise.

We denote the original quantum circuit as M_0 , consisting of N locations. Each location is denoted by a triple $(\{q_0, \dots, q_i\}, U, t)$, where the set of q_j , $1 \leq j \leq 2$, are the qubits involved in the operation U at time t . U is restricted to one- and two-qubit gates for simplicity and can be the identity operation. We fix a computation code C which encodes one qubit in m qubits. To achieve a fault-tolerant circuit, we concatenate this code recursively n times to create the circuit M_n that simulates, to n levels of concatenation, the original circuit M_0 .

The main change that occurs when including locality constraints in the fault-tolerance derivation is that additional “move” operations and error correction need to be added. Secondly, the error-correction procedure needs to be made local. How the latter task is done and what overhead is required will depend very much on the code. We will not focus on this issue in this paper.

Consider a particular example of a location, for example a two-qubit gate. This gate gets replaced by a so-called 1-rectangle in M_1 , which consists of error correction on both blocks of qubits followed by the encoded gate operation, shown in Fig. 2.

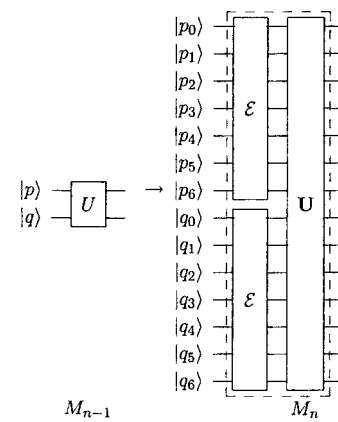


FIG. 2. The replacement rule for a two-qubit gate U . The dashed box represents a 1-rectangle. \mathcal{E} represents the error-correction procedure. U represents the encoded, fault-tolerant implementation of U .

In the local model, this replacement rule that we repeatedly apply to obtain the circuit M_n gets modified as in Fig. 3. While one block gets moved over a distance r , which we denote as a $\text{move}(r)$ operation, the other block is waiting. Next, the fault-tolerant implementation of the original gate is executed locally and then the block is moved back in place. We precede the move and wait operations by an error-correction routine, just as for the gate U . The model that we consider here assumes that the error levels induced by moving over distance r may be similar to the error levels due to the execution of the gate U . If moving is more error-prone, we may divide the distance r into shorter segments of length d , $r = \pi d$, and error-correct after every segment if necessary.

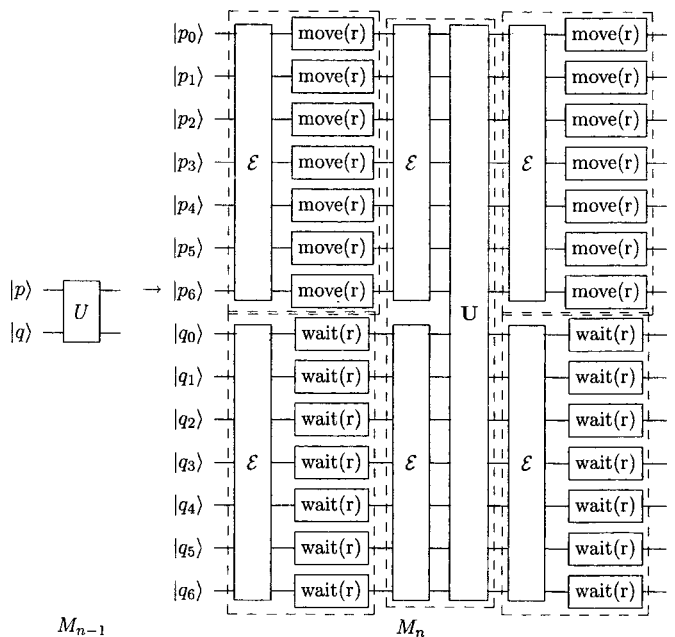


FIG. 3. The replacement rule for a local two-qubit gate U . Each dashed box represents an elementary 1-rectangle. \mathcal{E} represents the error-correction procedure. U represents the local fault-tolerant implementation of U . The replacement circuit, i.e., the composite 1-rectangle, contains five elementary 1-rectangles.

This modification and its effects will be considered when we make our detailed analysis in Sec. VI.

We see that in the local model, each location in M_{n-1} gets replaced by potentially more than one “elementary” 1-rectangle in M_n . Since this set of rectangles forms a logical unit, we will call the sequence of elementary 1-rectangles a *composite* 1-rectangle.

In the next section, we derive a rough lower bound on the threshold in the local model, depending on a scale parameter r .

A. Replacement rules

We formulate replacement rules for all possible other locations in the local model. We only consider locations that occur in the $[[7,1,3]]$ code. Additional rules may have to be formulated for other codes, but the threshold estimate in this section will not depend on these details. We assume in formulating these replacement rules that a one-qubit gate is never executed in parallel with a two-qubit gate (this is correct for the $[[7,1,3]]$ code that we study in Sec. VI); this means that the execution of the one-qubit gate is not delayed by the additional moving required for the two-qubit gate. Note that we have two types of memory locations, which we call wait locations, depending on the type of gate (one- or two-qubit gate) occurring in the same time slice. The figures depicting these rules can be found in Appendix A. Here is a list of the distinct locations in the local model, also listed in Table IV in Sec. IV A, and their replacement rules.

- (i) A one-qubit gate, depicted in Fig. 11.
- (ii) A one-qubit gate followed by a measurement, depicted in Fig. 12. We group a measurement with a one-qubit gate, since the replacement rule for a measurement by itself is just doing m measurements on m encoded qubits.
- (iii) A two-qubit gate U , depicted in Fig. 3.
- (iv) A wait location in parallel with only one-qubit gates, denoted as wait1 or $w1$. The replacement rule is the same as for a one-qubit gate (Fig. 11).
- (v) A wait location in parallel with two-qubit gates, denoted as wait2 or $w2$, depicted in Fig. 13.
- (vi) move(r), the operation which moves one qubit over distance r , where r depends on code properties, depicted in Fig. 14.
- (vii) wait(r), the operation which does nothing while another qubit moves over distance r , depicted in Fig. 15.

Note that our replacement rules enforce synchronization of gate operations and waiting periods. Note that at each new level of concatenation, every distance gets multiplied by the scale factor r , so that a move(r) gate becomes r move(r) 1-rectangles. We would like to stress that the goal here has been to choose a set of level-independent replacement rules that capture the overall behavior; architecture, code-dependent, and concatenation-dependent optimizations are not considered.

In order to apply the rules repeatedly, the encoded gate U is broken down into local elementary gates (potentially using additional swap gates) and the replacement rules are applied to these local gates.

B. Threshold estimate

As was noted in Ref. [12] and explicitly stated in Ref. [4], the formal derivation of a fault-tolerance threshold hinges on

three conditions (under the usual assumptions of having fresh ancillas and being able to operate gates in parallel). Fault paths are subsets of all locations on which faults occur. The conditions are, loosely speaking, the following:

- (i) “Sparse” fault paths (with few faults) lead only to sparse errors.
- (ii) “Sparse” fault paths give good final answers.
- (iii) Nonsparse fault paths have small probability/norm, going to zero with increasing concatenation level for initial failure probabilities/norms per location below some threshold value.

The first two statements are unchanged when going from a nonlocal to a purely local model of computation, assuming that the error-correction routines are made local in a fault-tolerant manner. It is the third condition whose derivation gets modified in this model. For concreteness, let us assume that our error model is a probabilistic error model, where each location undergoes a failure with some probability $\gamma(0)$. At an intuitive level, every location gets replaced by a composite 1-rectangle, which fails when at least one of the elementary 1-rectangles fails. If we assume that every type of 1-rectangle has a similar failure probability $\gamma(1)$, then the composite 1-rectangle which is most prone to failure is the one originating from the move(r) gate ($r \gg 5$) since it consists of r elementary 1-rectangles. In order to be below the threshold, the failure probability of the composite 1-rectangle has to be smaller than the failure probability of the original location, i.e.,

$$\gamma_0 \equiv \gamma(0) \geq 1 - [1 - \gamma(1)]^r \approx \gamma(1)r. \quad (1)$$

Let us assume that $A_{l,C}$ is (an upper bound on) the number of locations in an elementary 1-rectangle that has been made local. We say that a 1-rectangle fails if, say, more than k among these locations have faults. Here $k = \lfloor d/2t \rfloor$ for a code with spread t which can correct d errors. Thus $\gamma(1) \approx \binom{A_{l,C}}{k+1} \gamma(0)^{k+1}$ and we get the threshold condition

$$\gamma_{0,\text{crit}} = \frac{1}{\left[r \binom{A_{l,C}}{k+1} \right]^{1/k}}. \quad (2)$$

The difference with the nonlocal model is the appearance of r on the right-hand side of this equation. Note that the effects of locality *seem* to become effectively smaller for large k , i.e., for codes that can correct many errors. On the other hand, the scale factor r itself increases for codes that correct many errors, since the number of qubits in an encoded word and the size of the error-correcting machinery are larger. The $[[7,1,3]]$ code that we analyze in more detail in the next section does not entirely fit this analysis. The reason is that for the $[[7,1,3]]$ code, $d=1$ and $t=1$, causing k to be zero; this is because one can have one incoming error (a late error in the previous rectangle) and one early error in the rectangle, leaving two errors on the data, which $[[7,1,3]]$ cannot correct. However, a different analysis [13] for such codes shows that one-error events in bigger “overlapping” rectangles (which include error correction, gate operation, and error correction again) are acceptable for this code, so k actually equals 1. Thus we expect for the $[[7,1,3]]$ code that the threshold for the

local model scales as $1/r$, which we partially confirm later.

A more formal analysis uses the notion of n -rectangles in M_n . We state the definitions as given in Ref. [12] in Appendix B. In M_n , a composite n -rectangle originates from a single location in M_0 . The composite n -rectangle consists of at most r elementary n -rectangles. Each of these elementary n -rectangles consists of at most $A_{l,C}$ composite $(n-1)$ -rectangles, each of which again consists of at most r elementary $(n-1)$ -rectangles. Formally, we need to prove condition (iii) above, namely that the probability (assuming a probabilistic model) for sparse “good” faults gets arbitrarily close to 1 when we are below the threshold. Here we state the necessary lemma, which has an identical structure to the one in [12].

Lemma 1. If $\gamma_0 < \gamma_{0,\text{crit}}$, $\exists \delta > 0$ such that the probability $P(n)$ for the faults in a composite n -rectangle to be (n,k) -sparse is larger than $1 - \gamma_0^{(1+\delta)^n}$.

Proof. Let δ be such that

$$r \binom{A_{l,C}}{k+1} \gamma_0^{k+1} < \gamma_0^{1+\delta}. \quad (3)$$

For γ_0 below the threshold, we can find such a δ . We prove the lemma by induction on n . The probability for a composite 1-rectangle to have $(1,k)$ -sparse faults, i.e., all elementary 1-rectangles (of which there are at most r) have sparse faults, is at least

$$\left[1 - \binom{A_{l,C}}{k+1} \gamma_0^{k+1} \right]^r \geq 1 - r \binom{A_{l,C}}{k+1} \gamma_0^{k+1} > 1 - \gamma_0^{1+\delta}, \quad (4)$$

using Eq. (3). Assume the lemma holds true for n and we prove for $n+1$. For the faults in a composite $(n+1)$ -rectangle not to be $(n+1,k)$ sparse, there must at least be one elementary $(n+1)$ -rectangle in which the faults are not $(n+1,k)$ -sparse, which implies that in that rectangle there are at least $k+1$ composite n -rectangles which are not (n,k) -sparse. Thus,

$$\begin{aligned} P(n+1) &\geq \left[1 - \binom{A_{l,C}}{k+1} [1 - P(n)]^{k+1} \right]^r \\ &\geq 1 - r \binom{A_{l,C}}{k+1} [1 - P(n)]^{k+1}. \end{aligned} \quad (5)$$

Using the induction hypothesis and Eq. (3) then gives

$$P(n+1) > 1 - (\gamma_0)^{(1+\delta)^{n+1}}, \quad (6)$$

as desired. \square

We note that a similar analysis could be performed for any other noise model which is derived with the method used in Ref. [12], such as noise satisfying the exponential decay conditions or local non-Markovian noise [4]. The proof of condition (iii) in these cases needs to be altered to take into account the dependence on r .

IV. NONLOCAL FAULT TOLERANCE FOR THE SEVEN-QUBIT $[[7,1,3]]$ CODE

In order to make a good comparison between using a concatenated $[[7,1,3]]$ code in the local or nonlocal model, we

TABLE I. Types of locations and their failure probability symbols in the nonlocal analysis.

Location	Description	Failure Prob.
1	one-qubit gate	γ_1
2	two-qubit gate	γ_2
w	memory (wait)	γ_w
$1m$	one-qubit gate+measurement	γ_{1m}
p	preparation	γ_p

perform a fault-tolerance analysis for the nonlocal model. In Ref. [5], Steane performed such an analysis and we follow his analysis to a certain extent. At the end of this section, we summarize our findings for the nonlocal model. The goal is to produce a threshold in the right ballpark, taking into account various (but not all) details of the error-correction circuitry. The details of error correction [3,5,14,15] are depicted in Figs. 16–19 in Appendix C and can be described as follows. Error correction of a seven-qubit block consists of X - and Z -error correction denoted as \mathcal{X} and \mathcal{Z} . For both types of error correction, one prepares n_{rep} ancillas, using the \mathcal{G} network in Fig. 17. These ancillas are tested for X errors using the \mathcal{V} network in Fig. 18 and discarded if they fail the test. The probability for passing this test is called α . If they do pass the test, they can be used to collect the syndrome as in Fig. 19. If the first collected syndrome is zero, then no further syndromes are collected (the idea being that it is likely that there is no error on the data). The probability for a zero syndrome is called β . If the syndrome is nonzero, an additional $s-1$ syndromes are collected. These s syndromes are then compared, and if there are s' among them which agree, then error recovery, denoted by \mathcal{R} , is done according to this syndrome. If there are no s' which agree, no error correction is done and in our model (see [5] for modifications) we do not use these error syndromes in any subsequent error correction.

Let us now consider the problem of determining the fault-tolerance threshold by semianalytical means. At the base level, we start with a vector of failure probabilities of the locations in our model which we call $\vec{\gamma}(0)$. In our case, we have the following five kinds of locations l : a one-qubit gate ($l=1$) with failure probability $\gamma_1 \equiv \gamma_1(0)$, a two-qubit gate ($l=2$) with failure probability γ_2 , a wait location ($l=w$) with failure probability γ_w , a one-qubit gate followed by measurement ($l=1m$) with failure probability γ_{1m} , and a $|0\rangle$ preparation location with failure probability γ_p . Table I lists these types of locations in the nonlocal model.

There are several ways in which one can do a fault-tolerance analysis. The first method is to perform a Monte Carlo simulation (see, for example, [5,7,16]) of a sequence of operations for some level of concatenation and deduce a failure or crash probability. The advantage of this method is that it takes into account incoming errors into rectangles and then it otherwise exactly mimics the failure probability in the real quantum computation. The disadvantage, in particular for large codes, is that it is hard to simulate high levels of concatenation, since the size of the classical computation

scales exponentially with concatenation level. As we will discuss in a moment, and demonstrate in our studies, simulating more than one level of concatenation is often needed to nail down the threshold.

The second method is a semianalytical one, which we follow, to obtain an approximate probability flow equation. Due to concatenation, each location is represented by a rectangle, which has some probability of failure, meaning that at the end of the rectangle there are more errors on the data than the code can correct. Thus after one level of concatenation, the probability vector $\vec{\gamma}(0)$ is mapped onto $\vec{\gamma}(1)$, and we repeat this procedure. We say that the original vector $\vec{\gamma}(0)$ is below the threshold if $\vec{\gamma}(n) \rightarrow 0$ for large enough n . The drawback of this kind of analysis is that careful approximations need to be made in order to estimate the failure probability function of a rectangle, since a complete analysis may be too complicated. Furthermore, the analysis does not deal so well with incoming errors, since we look at one 1-rectangle at a time. The advantage is that it is easy to look at high levels of concatenation.

In the next section, we approximate the failure probability function $\gamma_l(n) = \mathbf{F}_l(\vec{\gamma}(n-1))$ for the different types of 1-rectangles. First, we describe the modeling assumptions we have chosen.

A. Modeling choices

(i) We assume that the time it takes to do a measurement is the same as the one-qubit gate time and that classical postprocessing does not take any additional time.

(ii) We have chosen to call a one-qubit gate followed by a measurement a single location. The reason is that there is no explicit concatenation step for measurement, since each measurement just gets replaced by seven measurements and classical postprocessing to correct for errors. We choose to set the failure probability of a measurement $\gamma_m = \gamma_1$. Thus the failure probability for the location $1m$ is approximated as $\gamma_{1m} \approx \gamma_1 + \gamma_m$. As it turns out, there are no two-qubit gates followed by measurement in the $[[7,1,3]]$ error-correction routines, and a wait or memory location of any length followed by a measurement is just measurement, since there is no reason to wait.

(iii) A preparation of the state $|0\rangle$ is a preparation location with a preparation failure probability γ_p . For simplicity, we may set $\gamma_p = \gamma_1$. At the next level of concatenation, this location will be replaced by an encoding circuit. Preparing an encoded $|0\rangle$ can be done by first performing error correction on an arbitrary state which projects the state into the code space and then measuring the eigenvalue of the encoded Z operator fault-tolerantly and correcting if this eigenvalue is -1 . Even though the last procedure, done fault-tolerantly, will be more involved than the execution of a transversal one-qubit gate, we assume that the encoding/preparation rectangle is of the one-qubit gate type. In other words, we do not use a separate replacement rule for a preparation location.

(iv) We will typically work in the regime where $\gamma_w < \gamma_{1,2}$, perhaps an order of magnitude smaller.

(v) We assume (here and in the local model) that our

quantum circuit contains only controlled- Z (C^Z), controlled-NOT (C^X), and Hadamard gates (H). Note that these can all be executed transversally. Of course, in order to make the computation universal, one would also need, e.g., a Toffoli gate or $\pi/8$ rotation. We believe that the inclusion of the $\pi/8$ gates would not alter the threshold in the local model very much. The reason is that (1) error correction does not need the $\pi/8$ gate and thus $\pi/8$ gates are fairly rare, (2) the $\pi/8$ gate, as a one-qubit gate, can be executed locally, and (3) the failure probability for the 1-rectangle of the $\pi/8$ gate is probably similar or lower than that of the two-qubit gate since it involves only one data block (and some ancillary state). As it turns out, already the inclusion of the two-qubit gates has a sizable effect on the threshold estimate.

The error-correction procedure as described in the previous section is not of fixed size; for example, it depends on the number of syndromes collected and whether we do a recovery operation. Here are some choices that we make which directly affect how we calculate the failure probability in the next section. These assumptions are not exactly the same as the ones made in Ref. [5]:

(i) The procedures for error correction are of course parallelized as much as possible to reduce errors due to waiting. As can be seen in the figures, the syndrome collection network \mathcal{S} (Fig. 19) then takes three time steps, the network \mathcal{G} (Fig. 17) has five time steps, and \mathcal{V} (Fig. 18) has six time steps. We assume that the four verification bits are prepared while the \mathcal{G} routine takes place.

(ii) We choose s , the maximum number of syndromes collected, to be $s=3$ and $s'=2$.

(iii) In every round of the computation, we assume that a nonzero syndrome occurs somewhere, so that in order to keep the network synchronized, the other data blocks have to wait for the additional $s-1$ syndromes to be collected. We take these wait locations into account.

(iv) We assume that a sufficient number n_{rep} of new ancillas is prepared in parallel *before* the beginning of each error-correction routine. We set $n_{\text{rep}} = \lfloor s/\alpha \rfloor$, so that on average we have enough ancillas for error correction. We assume that the ancillas are prepared during the previous error-correction procedure so that the data do not have to wait in order to be coupled to the ancillas. These assumptions are a bit too optimistic, since a nonlocal ancilla preparation and verification routine, see Figs. 17 and 18, takes 11 time steps, while three syndrome collection routines, see Fig. 19, take nine time steps in total (and this will be worse in the local version of these procedures since ancillas have to be “moved in place” to couple to the data).

(v) We assume that the prepared ancillas for the last $s-1$ syndrome collections have to wait before the previous syndrome collections are done. This could potentially be avoided, but we may as well include some extra wait locations since other approximations may be too optimistic.

(vi) In principle, we may not have enough syndromes in agreement, so that no error correction is performed, and secondly we could have enough syndromes agreeing but the syndrome may be faulty so that we do a faulty recovery operation. The latter probability may be quite small since errors have to “conspire” to make a faulty but agreeing syndrome, so we will neglect this source of errors. If we choose

TABLE II. Different sources of failure and their contribution to the failure probability. Here $\delta_{\text{anc}} = 1 - \text{P}(\text{no } X | \text{pass})$, where $\text{P}(\text{no } X | \text{pass}) = \text{P}(\text{pass and no } X) / \alpha$ and $\text{P}(\text{pass and no } X)$ is the probability that an ancilla passed verification *and* has no X errors on it. This probability is estimated in Sec. IV C. The probability γ_{ws} for obtaining a wrong majority syndrome is assumed to be 0 in our analysis.

Source	δ	N
Propagation from a verified ancilla with X error	δ_{anc}	$s_x + s_z$
Fault in C^Z or C^X in \mathcal{S}	γ_2	$7(s_x + s_z)$
Memory faults on data at the end of \mathcal{S}	γ_w	$14(s_x + s_z)$
Memory faults on data during \mathcal{R}	γ_w	$6(\delta_{s_z, s} + \delta_{s_x, s})$
Fault in gate of \mathcal{R}	$\gamma_1 + \gamma_{\text{ws}}$	$\delta_{s_z, s} + \delta_{s_x, s}$
Memory faults on data when $s=1$	γ_w	$21(s-1)(\delta_{s_z, 1} + \delta_{s_x, 1})$
X errors on ancillas waiting for \mathcal{S}	γ_w	$21s(s-1)(\delta_{s_z, s} + \delta_{s_x, s})/2$
Encoded gate error in rect. of type l	γ_l	7

not to do error correction, we may have more incoming errors in the next routine; we do model incoming errors to some extent in our estimation of α and β , but we will not consider this source of errors separately.

In the estimation of the failure probability we always assume that faults do not cancel each other.

We are working with the probabilistic error model where each gate or location can fail with a certain probability. For a location on a single qubit that fails with probability γ , we say that an X , Y , or Z error occurs with probability $\gamma/3$. We will use this distinction between X , Y , and Z errors in our estimation of α and β in the next section.

B. Failure probability

For the $[[7,1,3]]$ code, failure of a 1-rectangle means that two or more errors occur on data qubits during the execution of the operations in the 1-rectangle. This could happen when we have a single incoming error and, say, a syndrome collection gate, such as C^Z , introduces an additional error on the data and the ancilla. In estimating the failure probability, we do not take into account incoming errors since below the threshold the probability for incoming errors should typically be small. The circuits are designed such that if there are no incoming errors and a single fault occurs in the 1-rectangle, that fault will typically either not affect the data, or will be corrected. Only if the fault occurs late in the routine, say in the encoded gate operation, will the fault be passed on to the next error-correction routine. Thus we assume that two faults affecting the data are needed for failure. First, let us consider those 1-rectangles which involve a single data block, i.e., $l=1, 1m, p, w$. Let $\mathbf{F}_l[s_x, s_z](\tilde{\gamma})$ be the failure probability for a rectangle of type l when s_x and s_z syndromes in \mathcal{X} and \mathcal{Z} , respectively, are calculated. We can write

$$\begin{aligned} \gamma_l(n) = & \beta^2 \mathbf{F}_l[1, 1](\tilde{\gamma}(n-1)) + 2\beta(1-\beta) \mathbf{F}_l[s, 1](\tilde{\gamma}(n-1)) \\ & + (1-\beta)^2 \mathbf{F}_l[s, s](\tilde{\gamma}(n-1)). \end{aligned} \quad (7)$$

From now on, we will omit the dependence on concatenation level, i.e., we express \mathbf{F}_l in terms of γ_j . Let $\text{P}(e^+ \in T, s_x, s_z)$ be the probability of e or more faults on the data block due to source T when s_x and s_z syndromes are calculated. We may model

$$\text{P}(1^+ \in T, s_x, s_z) = 1 - [1 - \delta(T)]^{N(T, s_x, s_z)}, \quad (8)$$

where $\delta(T)$ is the failure probability of the particular location (or event) in T which causes the fault and $N(T, s_x, s_z)$ counts the number of places in T where the fault can occur. Similarly, we have

$$\begin{aligned} \text{P}(2^+ \in T, s_x, s_z) = & 1 - [1 - \delta(T)]^{N(T, s_x, s_z)} - \delta(T)N(T, s_x, s_z) \\ & \times [1 - \delta(T)]^{N(T, s_x, s_z)-1}. \end{aligned} \quad (9)$$

In Table II, we describe the possible sources of faults on the data and their values for δ and N . For failure to occur, we can typically have one fault due to source I and one due to source J or two faults due to source I . In other words, we approximate

$$\begin{aligned} \mathbf{F}_l[s_x, s_z] \approx & \sum_{I>J} \text{P}(1^+ \in I, s_x, s_z) \text{P}(1^+ \in J, s_x, s_z) \\ & + \sum_I \text{P}(2^+ \in I, s_x, s_z). \end{aligned} \quad (10)$$

Some of the parts of the first term give somewhat of an overestimate, since a single fault in, say, \mathcal{X} and a single fault in \mathcal{Z} do not necessarily lead to a failure. Also, note that we are overcounting some higher-order fault terms, but these should be small. Note that the l dependence of the right-hand side of Eq. (10) only appears in the terms that involve the faults due to encoded gate operations listed in Table II. Note that we do not distinguish between X , Y , or Z errors in estimating the failure probability.

For an $l=2$ (C^X or C^Z) 1-rectangle, the analysis is slightly more involved. Let $\mathbf{F}[s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}]$ be the failure probability of the two error-correction routines on block 1 and 2 when s_{x_1} and s_{z_1} syndromes are computed for block 1 and s_{x_2} and s_{z_2} syndromes are computed for block 2 (without the subsequent gate operation). Let $m_j \in \{0, 1\}$ such that $m_j=0$ when $s_j=s$ and $m_j=1$ when $s_j=1$, where $j \in \{x_1, x_2, z_1, z_2\}$ and s is the number of syndrome measurements. We can then write

TABLE III. Types of errors in various subroutines that should not occur when ancilla passes verification and should have no X or no Z errors. When we write Z , it implies that neither Z nor Y should occur, since Y is both an X and Z error. Late wait indicates the wait locations on ancilla qubits that are finished interacting with the verification qubits. Early wait locations indicate the wait locations that occur before the last interaction with the verification bits. Verification wait locations indicate the wait locations that occur on the verification qubits. Strictly speaking, for the contribution to $\mathbb{P}(\text{pass and no } Z)$ we should distinguish between early and late wait errors on the verification qubits; we approximate this by requiring no types of errors on the verification qubit wait locations.

	Prep. ver. bits	$H+$ meas. ver. bits	From \mathcal{G}	Early wait in \mathcal{V}	Late wait in \mathcal{V}	Ver. wait in \mathcal{V}
$\mathbb{P}(\text{pass and no } Z)$	X, Z	X	X, Z	X, Z	Z	X, Z
$\mathbb{P}(\text{pass and no } X)$	Z	X	X	X	X	Z

$$\begin{aligned} \gamma_2(n) = & \sum_{s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}=1, s} (\beta)^{m_{x_1} + m_{x_2} + m_{z_1} + m_{z_2}} \\ & \times (1 - \beta)^{4 - m_{x_1} - m_{x_2} - m_{z_1} - m_{z_2}} \mathbf{F}[s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}](\tilde{\gamma}(n-1)). \end{aligned} \quad (11)$$

Let $\mathbf{F}(s_x, s_z)$ be the failure probability of one error-correction routine when s_x and s_z syndromes are calculated, i.e., it is Eq. (10) with the additional constraint that the source is never the encoded gate. Let $\mathbb{P}(1^+ \in T, s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2})$ be the probability of one or more faults anywhere due to source T in the two error-correction routines calculating $s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}$ syndromes, that is, the number N in Eq. (8) gets modified to $N(T, s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2})$, which is similar to the ones in Table II except that we add the contributions from both error corrections. Then for C^A , where $A=X$ or $A=Z$, we approximate

$$\begin{aligned} \mathbf{F}[s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}] \approx & \mathbb{P}(2^+ \in C^A) \\ & + 7\gamma_2(1 - \gamma_2)^6 \sum_{I \neq G} \mathbb{P}(1^+ \in I, s_{x_1}, s_{z_1}, s_{x_2}, s_{z_2}) \\ & + (1 - \gamma_2)^7 [\mathbf{F}(s_{x_1}, s_{z_1}) + \mathbf{F}(s_{x_2}, s_{z_2})]. \end{aligned} \quad (12)$$

The first term represents the contribution from having two or more faults in the two-qubit gate, the second term represents one gate fault and one or more faults somewhere in the error-correction routines, and the third term represents no faults in the gates and two or more in either the error correction on block 1 or block 2.

C. Estimation of α and β

Our next task is to provide estimates for α , the probability of an ancilla passing verification, and β , the probability of obtaining a zero syndrome. One can find another estimation of α and β in Ref. [5]. Similar to the failure probability, α and β are functions of concatenation level, i.e., $\mathbf{F}_i(\tilde{\gamma}(n-1))$ involves the functions $\alpha(n-1) \equiv \alpha(\tilde{\gamma}(n-1))$ and $\beta(n-1) \equiv \beta(\tilde{\gamma}(n-1))$. In the following, we omit the concatenation level dependence, i.e., we express α and β in terms of γ_i .

For CSS codes, error correction is performed in two steps. While X and Z errors are detected in only one of the two steps, Y errors contribute to both. Hence if X, Y, Z errors are equally likely, the probability to detect an error is $2/3p$ for each step, where p denotes the total error probability.

In the following paragraph we will speak of events that are detected as X errors or Z errors. Thus if a Y error occurs, this results in both an X and Z error event.

The fraction α of ancillas that pass verification can be calculated as

$$\begin{aligned} \alpha = & \mathbb{P}(\text{pass and no } X) + \mathbb{P}(\text{pass and } X) \\ = & \mathbb{P}(\text{pass and no } X) + \mathbb{P}(\text{pass and no } Z) \\ & - \mathbb{P}(\text{pass and no } Z, \text{ no } X) + \mathbb{P}(\text{pass and } Z, X). \end{aligned} \quad (13)$$

The last probability we approximate as $\mathbb{P}(\text{pass and } Z, X) \approx 0$. Table III shows what types of errors should be avoided in order to have a passing ancilla and no X or no Z errors.

For the C^Z gates, the exact contributions from various errors is harder to estimate (one has to examine the cases more carefully), so we approximate this by saying that in order to have a passed ancilla and no Z or no X error on the ancilla, all C^Z gates have to have no errors. This implies that

$$\begin{aligned} \mathbb{P}(\text{pass and no } Z) = & (1 - \gamma_p)^4 (1 - \gamma_1)^4 (1 - 2\gamma_{1m}/3)^4 \\ & \times \prod_{i \in \mathcal{G}} (1 - \gamma_i)^{N(i \in \mathcal{G})} (1 - 2\gamma_w/3)^{26} \\ & \times (1 - \gamma_w)^6 (1 - \gamma_2)^{13}, \end{aligned} \quad (14)$$

and, slightly different,

$$\begin{aligned} \mathbb{P}(\text{pass and no } X) = & (1 - 2\gamma_p/3)^4 (1 - 2\gamma_1/3)^4 (1 - 2\gamma_{1m}/3)^4 \\ & \times \prod_{i \in \mathcal{G}} (1 - 2\gamma_i/3)^{N(i \in \mathcal{G})} (1 - 2\gamma_w/3)^{32} \\ & \times (1 - \gamma_2)^{13}. \end{aligned} \quad (15)$$

Assuming that none of the possible faults occurs, then we can say that

$$\mathbb{P}(\text{pass and no } Z, \text{ no } X) \approx \prod_i (1 - \gamma_i)^{N(i \in \mathcal{G}, \mathcal{V})}. \quad (16)$$

From these estimates, we can calculate α .

Next we approximate β , the probability of obtaining a zero syndrome, in an X -error-correction routine as

$$\begin{aligned} \beta \approx & \mathbb{P}(\text{no } Z \text{ errors no anc.} | \text{ancilla passed}) \\ & \times \mathbb{P}(\text{no } Z \text{ errors on syn. due to } \mathcal{S}) \\ & \times \mathbb{P}(\text{no } X \text{ error coming into } \mathcal{A}). \end{aligned} \quad (17)$$

We have

$$P(\text{no } Z \text{ errors on anc.} | \text{ancilla passed}) = P(\text{pass and no } Z) / \alpha. \quad (18)$$

It is easy to estimate

$$P(\text{no } Z \text{ errors on syn. due to } \mathcal{S}) = (1 - 2\gamma_2/3)^7 (1 - 2\gamma_{1m}/3)^7. \quad (19)$$

Thirdly, we have

$$\begin{aligned} &P(\text{no incoming } X \text{ error in } \mathcal{X}) \\ &= P(\text{no incoming } X \text{ error in } \mathcal{Z}) \\ &\quad \times [\beta P(\mathcal{S}_1 \in \mathcal{Z} \text{ leaves no } X \text{ error}) \\ &\quad \times P(\text{no } X \text{ err. on waiting data}) \\ &\quad + (1 - \beta) P(\mathcal{S}_{1,2,\dots,s} \in \mathcal{Z} \text{ leave no } X \text{ error})], \end{aligned} \quad (20)$$

What is the probability P (no incoming X errors in \mathcal{Z})? If we assume that the previous \mathcal{X} did its job, i.e., removed the errors, the only source of error is the gate that was done after \mathcal{X} . Since we do not know which gate was performed, we assume that the most error-prone gate occurred. Since all gates in our model are transversal, we approximate

$$P(\text{no incoming } X \text{ error in } \mathcal{Z}) \approx [1 - 2(\max_i \gamma_i)/3]^7. \quad (21)$$

We further estimate

$$\begin{aligned} &P(\mathcal{S}_1 \in \mathcal{Z} \text{ leaves no } X \text{ error}) \\ &= P(\mathcal{S}_1 \text{ gives no } X \text{ errors on data}) \\ &\quad \times P(\text{no } X \text{ errors on anc.} | \text{anc. passed}), \end{aligned} \quad (22)$$

where

$$P(\mathcal{S}_1 \text{ gives no } X \text{ errors on data}) = (1 - 2\gamma_2/3)^7. \quad (23)$$

Lastly, we have

$$P(\text{no } X \text{ errors on anc.} | \text{anc. passed}) = P(\text{pass and no } X) / \alpha. \quad (24)$$

We also estimate

$$\begin{aligned} &P(\mathcal{S}_{1,2,\dots,s} \in \mathcal{Z} \text{ leave no } X \text{ error}) \\ &\approx P(\mathcal{S}_1 \in \mathcal{Z} \text{ leave no } X \text{ error})^s. \end{aligned} \quad (25)$$

This estimate does not include the fact that the prepared ancillas may have to wait (and degrade) until they are coupled to the data. If there is only one syndrome collection, the data may have to wait until other full syndrome collections are done. We take this into account with

$$P(\text{no } X \text{ err. on waiting data}) = (1 - 2\gamma_w/3)^{21(s-1)}. \quad (26)$$

Thus, using Eqs. (17)–(26), we arrive at a closed formula for β .

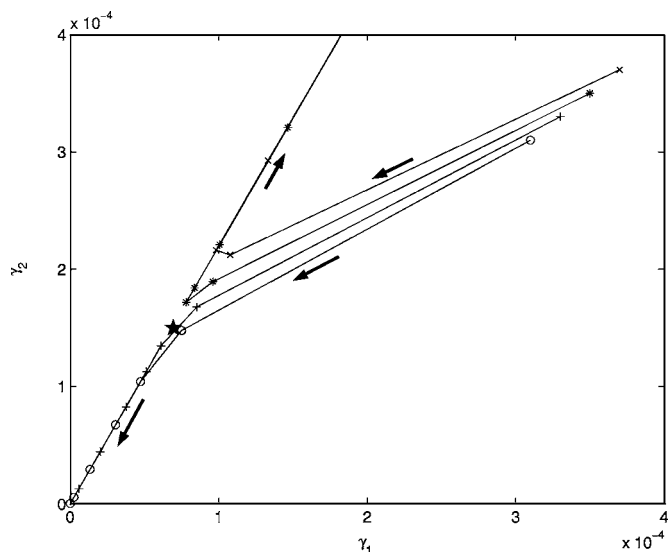


FIG. 4. Flows of the one- and two-qubit failure rates under concatenation in the nonlocal model. We initially set $\gamma_1 = \gamma_2 = \gamma_p = \gamma_m = 10 \times \gamma_w$. Four starting values are shown, two below threshold and two above. The initial flow is evidently very similar regardless of whether the map is above or below threshold. The hyperbolic structure of the flow is controlled by an unstable fixed point of the map at $\gamma_1 = \gamma_w = \gamma_{1m} = \gamma_p = 0.69 \times 10^{-4}$ and $\gamma_2 = 1.50 \times 10^{-4}$, shown as the black “star” symbol. Note that the line onto which these flows asymptote has γ_2 very close to $2 \times \gamma_1$.

V. NUMERICAL THRESHOLD STUDIES FOR THE NONLOCAL MODEL

We have used the formulas for failure probabilities, α , and β of the last two subsections to quantify the fault-tolerance threshold for the nonlocal model. We study the effect of the repeated application of the map $\mathbf{F}_l(\vec{\gamma})$, namely the dependence of the parameters on concatenation level. This is a four-dimensional map—there are five probability variables, but under our assumptions γ_1 and γ_p behave identically. This four-dimensional flow is of course impossible to visualize directly, but two-dimensional projections of these flows prove to be very informative.

In Figs. 4–6, we show three instances of such a projected flow in the γ_1 - γ_2 plane. In Fig. 4, we have initially taken the memory failure probability to be 10% of the gate failure probability and one- and two-qubit gate failure probabilities to be equal; that is, prior to concatenation, we take $\gamma_1 = \gamma_2 = \gamma_p = \gamma_m = 10 \times \gamma_w$. In Fig. 5, we initially take $\gamma_1 = 0.25 \times \gamma_2 = \gamma_p = \gamma_m = 10 \times \gamma_w$. In Fig. 6, we initially take $\gamma_1 = 2.0 \times \gamma_2 = \gamma_p = \gamma_m = 10 \times \gamma_w$. With these initial choices, we look at the flows as we concatenate the map. Figures 4–6 show the behavior as the threshold noise value is crossed. As is common in renormalization-group flows, these have a hyperbolic character; the flows all asymptote to a one-dimensional line (for which, as can be seen in the figures, $\gamma_2 \approx 2\gamma_1$). In Fig. 4, for all initial points up to $\gamma_2 \leq 3.35 \times 10^{-4}$, the flows follow this line to the origin, indicating successful fault-tolerant computation; for all higher failure rates the flows asymptote to one, indicating the failure of error correction.

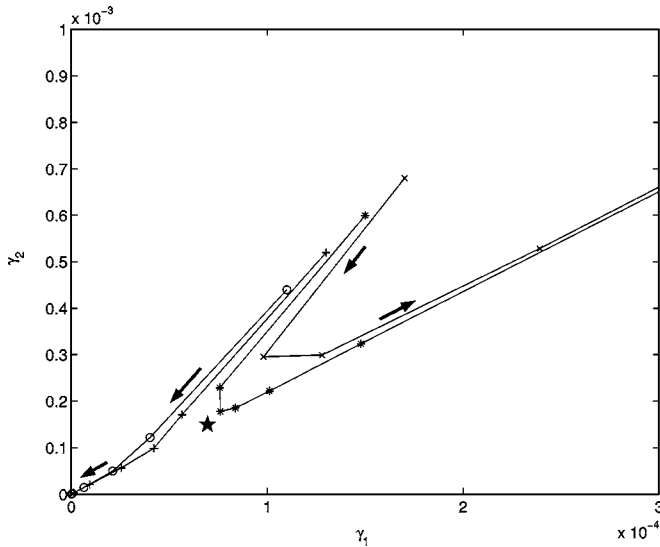


FIG. 5. Flows of the one- and two-qubit failure rates under concatenation in the nonlocal model. We initially set $\gamma_1=0.25 \times \gamma_2=\gamma_p=\gamma_m=10 \times \gamma_w$. Four starting values are shown, two below threshold and two above. The initial flow is evidently very similar regardless of whether the map is above or below threshold. The hyperbolic structure of the flow is controlled by an unstable fixed point of the map at $\gamma_1=\gamma_w=\gamma_{1m}=\gamma_p=0.69 \times 10^{-4}$ and $\gamma_2=1.50 \times 10^{-4}$, shown as the black “star” symbol. Note that the line onto which these flows asymptote has γ_2 very close to $2 \times \gamma_1$.

The whole character of the flow is set by the presence of an unstable fixed point at the black star, at approximately $\gamma_1=\gamma_w=\gamma_{1m}=\gamma_p=0.69 \times 10^{-4}$ and $\gamma_2=1.50 \times 10^{-4}$ in Figs. 4–6. It is evident that the linearized map around this point has one positive (unstable) eigenvalue and four negative ones.

The threshold, of course, is not a single number; it is the separatrix between points in the four-dimensional space of failure probabilities that flow to the origin upon concatenation, and those that flow to one. This separatrix is a three-dimensional hypersurface. A one-dimensional cut through this hypersurface is shown in Fig. 7. This is shown in the plane of memory failure γ_w versus all other failures, with all these rates taken to be the same: $\gamma_{\text{else}}=\gamma_1=\gamma_2=\gamma_p=\gamma_m$. The threshold curve (indicated with black “dot” symbols) is nearly approximated by a straight line.

In Ref. [5], it has been suggested that a reasonable estimate for the threshold can be obtained by finding the failure rate for which the error is unchanged after the first concatenation of the error-correcting code. Figures 4 and 7 indicate that this rule of thumb actually has limited value (see [20]). For all plotted initial points in Fig. 4, the failure probabilities go down after one level of concatenation. However, after one more level of concatenation, two of the failure probabilities go up again, indicating that those two initial points were above threshold.

In Fig. 7, we investigate this further by plotting three “pseudothresholds” along with the actual threshold curve. These pseudothresholds are the lines along which γ_1 , γ_2 , and γ_w are unchanged after one iteration of the map. Obviously,

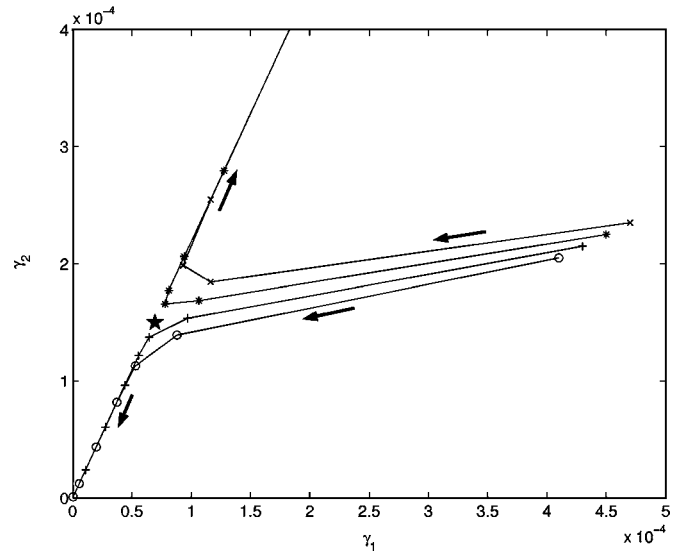


FIG. 6. Flows of the one- and two-qubit failure rates under concatenation in the nonlocal model. We initially set $\gamma_1=2.0 \times \gamma_2=\gamma_p=\gamma_m=10 \times \gamma_w$. Four starting values are shown, two below threshold and two above. The initial flow is evidently very similar regardless of whether the map is above or below threshold. The hyperbolic structure of the flow is controlled by an unstable fixed point of the map at $\gamma_1=\gamma_w=\gamma_{1m}=\gamma_p=0.69 \times 10^{-4}$ and $\gamma_2=1.50 \times 10^{-4}$, shown as the black “star” symbol. Note that the line onto which these flows asymptote has γ_2 very close to $2 \times \gamma_1$.

these three are very different from one another and from the true threshold curve. Rather than being straight, the pseudothresholds are very curved. They curve in to the origin for a very simple reason: if γ_1 and γ_2 are initially zero, then regardless of the value of γ_w (i.e., anywhere along the y axis of the plot), γ_1 and γ_2 become nonzero after one iteration, so every point on the y axis is above these pseudothresholds. The corresponding statements hold about the x axis for the γ_w pseudothreshold.

We note that, particularly in the region where $\gamma_w \ll \gamma_{\text{else}}$, the γ_1 pseudothreshold is a very substantial overestimate of the true threshold. On the plot we indicate the line for which memory failure is one-tenth of gate failure, a situation studied extensively by Steane [5]. The γ_1 pseudothreshold is around $\gamma_{\text{else}}=1.2 \times 10^{-3}$ (near the threshold value estimated by Steane), while the true threshold is at $\gamma_{\text{else}}=0.34 \times 10^{-3}$, about a factor of 4 lower. Looking at a wider range of initial failure rate values, we find that the initial point $\vec{\gamma}(0)$ is below its true threshold whenever all of the γ 's decrease on the first iteration of the map. However, this rule of thumb is much too conservative—there are large regions of this plot for which one or more of the γ 's initially increase, and yet we are below threshold.

It appears that distinguishing logical one-qubit gate errors from logical two-qubit gate errors has an important quantitative effect on our threshold estimates; the γ_2 curve turns upward much more rapidly than the γ_1 curve if we are near but above the threshold, and, in the vicinity of the fixed point in Figs. 4 and 5, γ_2 is twice as large as γ_1 . We see that this factor of 2 arises from a very simple cause: the rectangle describing the replacement rule for the two-qubit gate, Fig.

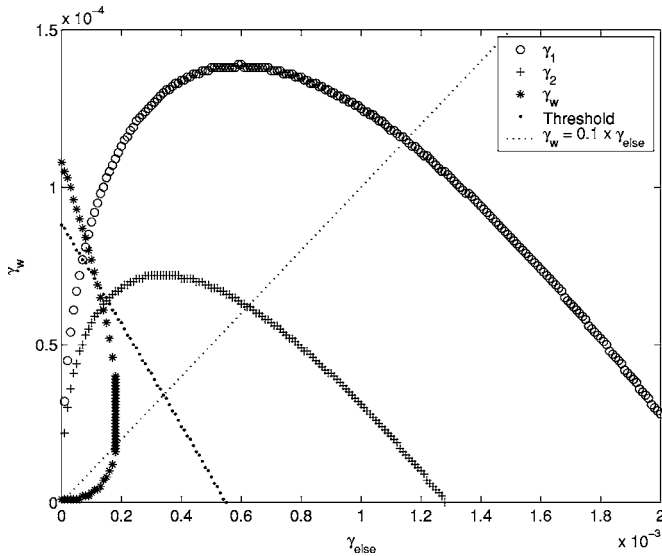


FIG. 7. The threshold line and pseudotreshold curves shown in the plane defined by the memory failure rate γ_w and all other failure rates $\gamma_{else} = \gamma_1 = \gamma_2 = \gamma_p = \gamma_m$. The pseudotreshold is defined as the line along which one of the failure rates remains unchanged after the first iteration of the map. Closer to the origin, this failure rate decreases; farther away, it increases. The pseudotresholds for γ_1 , γ_2 , and γ_w are shown. We note that along the line (dotted) for which $\gamma_w = 0.1 \times \gamma_{else}$, a popular condition in earlier studies, the gate pseudotresholds, particularly for the one-qubit gate failure rate, are much higher than the true threshold.

3, has two error-correction blocks that can fail. Is this factor of 2 simply an artifact of how we group the encoded computation into rectangles? It is clear that the answer is no; for the two-qubit gate, the key fact is that the failure of either error-corrected block will cause the entire encoded two-qubit gate, and the two encoded qubits emerging from it, to be faulty. It appears that this is the key reason that the differing behavior of one- and two-qubit gates under concatenation should be taken into account.

For memory errors, the story is rather different: we see that for large parts of Fig. 7 which are below threshold, γ_w increases (substantially, in fact) under concatenation. This clearly arises from the fact that upon encoding, a waiting period is replaced with an error-correction step, with all its (noisy) one- and two-qubit gates. One might think, then, that it might be desirable to skip error correction upon concatenation of a memory location. While this may indeed be possible, it raises a danger that would require more extensive analysis to assess: since single errors would go uncorrected, the error rate of qubits fed into the following rectangle would be greater. A much more careful calculation of the effects of these passed-on errors would need to be done to determine if skipping error corrections would in fact be helpful.

Finally, we wish to note that the quantities α and β are actually quite close to 1 near the threshold values of the failure rates. For β , we can understand this in the following way: the probability of getting a nonzero syndrome, $1 - \beta$, is roughly the probability for a single fault among N_{syn} locations which make the syndrome nonzero, i.e., we can approximate it as $N_{\text{syn}} \gamma$. For this argument, we forget about any

distinctions between types of errors and types of rectangles, so the N_{syn} is some mean number of locations, and γ is some average failure rate. Now, a rough estimate of the threshold γ (see Sec. III B) is $1/\binom{N}{2}$, where N is the number of locations that can cause errors on the data, see Table II. When $N \sim N_{\text{syn}}$, which is the case, we have $\beta \approx 1 - 2/N$. Since N is somewhere between 100 and 200, we conclude that β should be well above 90%, and this is what we see. A similar discussion can be given for α . In some cases, at the pseudotreshold, the values of α and β are much smaller.

VI. THE LOCAL MODEL WITH THE $[[7,1,3]]$ CODE

There are two main modifications that take place if we demand that all gates be local. First, each error-correction procedure needs to be modified so that it only consists of local gates. In this paper, we do not consider the additional overhead that is incurred from making the error correction local. Second, we have to use the local replacement rules as given in Figs. 3 and 11–15.

The typical values for the scale factor r , which we will vary in our numerical analysis, can be estimated by considering how many qubits are in the error-correction routine. For a nonlocal routine this number of qubits (which includes one block of data qubits) is $k = 7 + 2 \times n_{\text{rep}}(7 + 3)$. In the regime (which we have found to be the relevant regime in the nonlocal numerical study) where $\alpha \rightarrow 1$, $n_{\text{rep}} \rightarrow 4$, this gives $k = 87$. Note that we count both the ancillas in \mathcal{X} and \mathcal{Z} since the \mathcal{X} ancillas will be prepared during the \mathcal{Z} routine. By making the error correction local (for example by using dummy qubits), this number will increase somewhat. Thus it seems that taking r in the range of 10–100 may be reasonable (for a two-dimensional architecture we may take $r \approx \lceil \sqrt{k} \rceil$, which would give $r = 10$). The operations that move qubits around over distance r are composed from operations that move over distance d , where $r = \tau d$ and τ is some integer. We assume that the failure probability scales linearly with distance (which is a good assumption for small errors), i.e., if a move(d) operation has failure probability γ_{md} then a move(r) operation has failure probability $\gamma_{mr} = \tau \gamma_{md}$.

As it turns out, in Steane's error-correcting procedure, there are almost no one-qubit gates that occur in parallel with a two-qubit gate. The only exception is the preparation of the verification bits in the state $|+\rangle$ that occurs during \mathcal{G} , but these can be prepared at the last convenient moment. This implies that the computation is always a sequence of move gates followed by local *in situ* gates. The modeling in Sec. III A shows that there are two types of wait locations, ones that originally occur while a two-qubit gate occurs and ones that occur during a one-qubit local gate. The wait locations of the first type get mapped onto much longer wait and error-correction procedures, since they have to wait until the data have been moved. We also assume that data have to be moved back in place for the next gate, but it may be more efficient to move them elsewhere so that they are ready for a possible next nonlocal gate.

In the upcoming analysis, we distinguish between the failure probabilities for composite and elementary rectangles denoted as $\tilde{\gamma}^c(n)$ and $\tilde{\gamma}^e(n)$. For $n=0$, we of course have

TABLE IV. Types of locations and their failure probability symbols in the local analysis.

Location	Description	Failure Prob.
1	one-qubit gate	γ_1
2	two-qubit gate	γ_2
w1	wait during one-qubit gate	γ_{w1}
w2	wait during two-qubit gate	γ_{w2}
md	move distance d	γ_{md}
wd	wait during move(d)	γ_{wd}
1m	one-qubit gate+measurement	γ_{1m}
p	preparation	γ_p

$\tilde{\gamma}^c(0) = \tilde{\gamma}^e(0)$. We enumerate the types of locations and their probabilities in Table IV.

We now discuss the required modifications of the nonlocal model as compared to the local analysis with the $[[7,1,3]]$ code.

A. Modifications in the failure probability estimation

Each location l gets replaced by a composite 1-rectangle denoted as R_l^c containing more than one elementary 1-rectangle, denoted as R_j^e . In order for the composite rectangle to fail, at least one of the elementary rectangles has to fail, or

$$\gamma_l^c(n) = 1 - \prod_{j|R_j^e \in R_l^c} [1 - \gamma_j^e(n)], \quad (27)$$

where the failure probabilities $\gamma_j^e(n)$ are calculated similarly as in the nonlocal model [see Eqs. (7)–(12)]. Table V lists the occurrences of elementary 1-rectangles in composite 1-rectangles. The elementary failure probabilities $\gamma_j^e(n)$ are again functions of the vector of composite failure probabilities $\tilde{\gamma}^c(n-1)$, i.e., $\gamma_j^e(n) = \mathbf{F}'_j(\tilde{\gamma}^c(n-1))$.

Now we list the necessary modifications to the failure probability of an elementary rectangle and the estimation of α , the probability of an ancilla passing verification, and β ,

TABLE V. Each location l becomes a set of 1-rectangles by concatenation. The table lists which types of elementary 1-rectangles are present in the composite 1-rectangle R_l^c based on the replacement rules of Figs. 3 and 11–15. The number between [] indicates how often the elementary 1-rectangle occurs inside the composite 1-rectangle.

l	$j R_j^e \in R_l^c$
1	1[1]
2	move(d) $[2\tau=2r/d]$, wait(d) $[2\tau]$, 2[1]
1m	1m[1]
p	p[1]
move(d)	move(d) $[r]$
wait(d)	wait(d) $[r]$
w1	w1[1]
w2	wait(d) $[2\tau]$, w2[1]

TABLE VI. Modified memory sources of failure and their contribution to the failure probability. We only list the sources that are different due to the distinction between $w1$ and $w2$; the other sources are unchanged.

Modified source	δ	N
Memory faults on data at the end of \mathcal{S}	γ_{w1}^c	$14(s_x + s_z)$
Memory faults on data during \mathcal{R}	γ_{w1}^c	$6(\delta_{s_z, s} + \delta_{s_x, s})$
Memory faults ($w1$) on data when $s=1$	γ_{w1}^c	$14(s-1)(\delta_{s_z, 1} + \delta_{s_x, 1})$
Memory faults ($w2$) on data when $s=1$	γ_{w2}^c	$7(s-1)(\delta_{s_z, 1} + \delta_{s_x, 1})$
X errors on ancillas waiting ($w1$) for \mathcal{S}	γ_{w1}^c	$14s(s-1)(\delta_{s_z, s} + \delta_{s_x, s})/2$
X errors on ancillas waiting ($w2$) for \mathcal{S}	γ_{w2}^c	$7s(s-1)(\delta_{s_z, s} + \delta_{s_x, s})/2$

the probability of obtaining a zero syndrome. Note that the failure probability is now a function of the composite failure probabilities at the lower level. First we list the modifications to Table II in Table VI. In the source “errors due to propagation from the ancilla,” we also need to use a modified α , β , and P (pass and no X), estimated in the next section.

For a rectangle that acts on a single block, i.e., $l=p, w1, w2, 1, 1m$, move(d), wait(d), we write, similar to Eq. (7),

$$\gamma_l^e(n) = \beta^2 \mathbf{F}'_l[1, 1](\tilde{\gamma}^c(n-1)) + 2\beta(1-\beta) \mathbf{F}'_l[s, 1](\tilde{\gamma}^c(n-1)) + (1-\beta)^2 \mathbf{F}'_l[s, s](\tilde{\gamma}^c(n-1)), \quad (28)$$

where the function \mathbf{F}'_l takes into account the modifications in the failure sources.

B. Modifications in α and β

In each of the expressions in Sec. IV C [see Eqs. (14)–(26)], we have to use the failure probabilities of the *composite* rectangles. Equations (14) and (15) change due to the distinction between $w1$ and $w2$ locations,

$$\begin{aligned} \text{P(pass and no Z)} &= (1 - \gamma_p^c)^4 (1 - \gamma_1^c)^4 (1 - 2\gamma_{1m}^c/3)^4 \\ &\quad \times \prod_{i \in \mathcal{G}} (1 - \gamma_i^c)^{N(i \in \mathcal{G})} \\ &\quad \times (1 - 2\gamma_{w2}^c/3)^{12} (1 - 2\gamma_{w1}^c/3)^{14} \\ &\quad \times (1 - \gamma_{w2}^c)^6 (1 - \gamma_2^c)^{13}, \end{aligned} \quad (29)$$

and, slightly different,

$$\begin{aligned} \text{P(pass and no X)} &= (1 - 2\gamma_p^c/3)^4 (1 - 2\gamma_1^c/3)^4 (1 - 2\gamma_{1m}^c/3)^4 \\ &\quad \times \prod_{i \in \mathcal{G}} (1 - 2\gamma_i^c/3)^{N(i \in \mathcal{G})} (1 - 2\gamma_{w2}^c/3)^{18} \\ &\quad \times (1 - 2\gamma_{w1}^c/3)^{14} (1 - \gamma_2^c)^{13}. \end{aligned} \quad (30)$$

Note that in Eq. (21) we maximize over all possible locations in this new model. We also distinguish between $w1$ and $w2$ in Eq. (26),

$$\begin{aligned} \text{P(no X err. on waiting data)} &= (1 - 2\gamma_{w1}^c/3)^{14(s-1)} \\ &\quad \times (1 - 2\gamma_{w2}^c/3)^{7(s-1)}. \end{aligned} \quad (31)$$

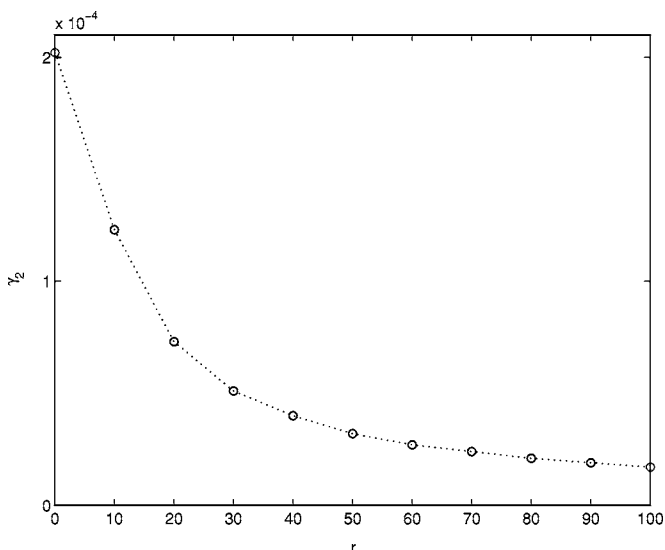


FIG. 8. Gate failure rate threshold vs the scale parameter r for the local model. We have taken $\gamma_1 = \gamma_2 = \gamma_m = \gamma_p$, $\gamma_{w1} = \gamma_{w2} = 0.1 \times \gamma_2$, $\gamma_{wd} = 0.1 \times \gamma_{md}$, and $\gamma_{md} = r/\tau \times \gamma_2$. τ , the frequency with which a qubit is error-corrected while being moved over distance r , is optimized in every case. The threshold follows very close to a $1/r$ dependence.

VII. NUMERICAL THRESHOLD STUDIES FOR THE LOCAL MODEL

By numerical iteration of the equations of the preceding sections, we study the repeated application of the map determined by encoding with the $[[7,1,3]]$ code in the local model. Although we now have an even higher-dimensional map than in the nonlocal studies (eight dimensions rather than five), the two cases are mathematically very similar; it is evident that the structure of the flows is again determined by the

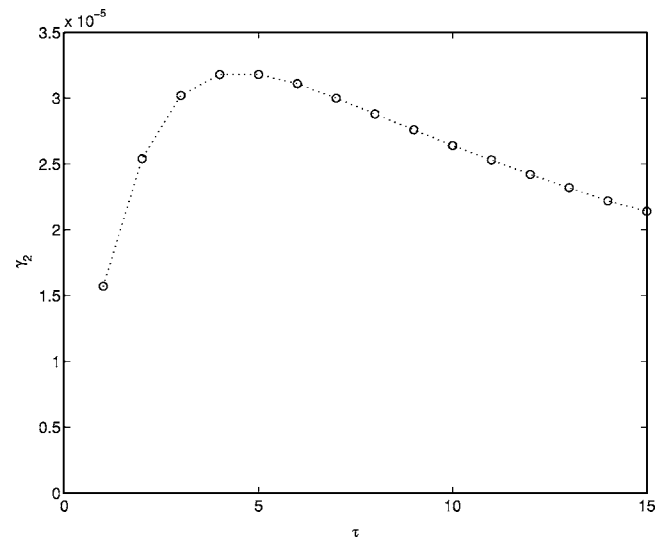


FIG. 9. Gate failure rate threshold vs τ , the frequency of error correction of a transported qubit, for $r=50$. As in Fig. 8, we have taken $\gamma_1 = \gamma_2 = \gamma_m = \gamma_p$, $\gamma_{w1} = \gamma_{w2} = 0.1 \times \gamma_2$, $\gamma_{wd} = 0.1 \times \gamma_{md}$, and $\gamma_{md} = r/\tau \times \gamma_2$. While not very strongly τ -dependent, the optimal threshold occurs at $\tau=4$.

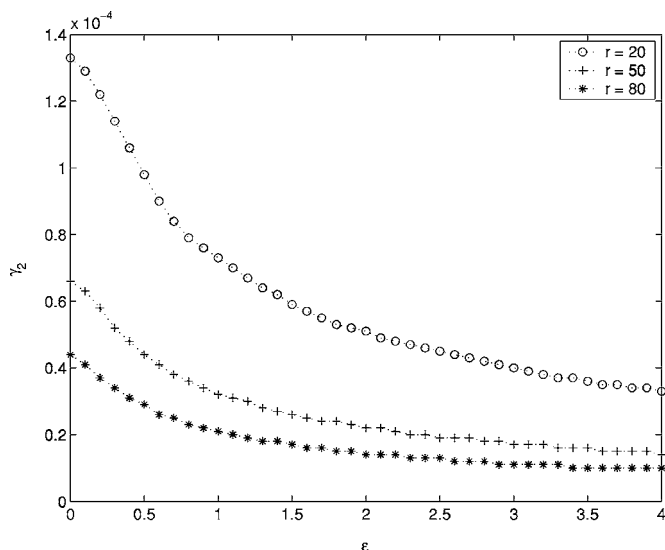


FIG. 10. Gate failure rate threshold vs ϵ , a parameter that measures the relative noise rate per unit distance for a qubit being moved. We initially set $\gamma_1 = \gamma_2 = \gamma_m = \gamma_p$, $\gamma_{w1} = \gamma_{w2} = 0.1 \times \gamma_2$, $\gamma_{wd} = 0.1 \times r/\tau \times \gamma_2$, and $\gamma_{md} = \epsilon r/\tau \times \gamma_2$. Scale parameters $r=20, 50$, and 80 are studied. At every point, τ is reoptimized. The dependence on ϵ is slow, evidently slower than $1/\epsilon$.

presence of an unstable fixed point with one positive eigenvalue (and in this case $8-1=7$ negative eigenvalues). An important difference is that the local map contains a free parameter, τ , the frequency of error correction while moving; we will exploit the freedom to optimize the fault-tolerance threshold in the numerical studies below.

Our first observation, illustrated in Fig. 8, is that the numerical values of the threshold failure probabilities can in fact be strongly affected by the need to transport qubits. For this figure we take physical failure rates $\gamma_1 = \gamma_2 = \gamma_m = \gamma_p$, $\gamma_{w1} = \gamma_{w2} = 0.1 \times \gamma_2$, $\gamma_{wd} = 0.1 \times \gamma_{md}$, and $\gamma_{md} = r/\tau \times \gamma_2 = d \times \gamma_2$. In other words, this means that the gate, measurement, and preparation failure rates are taken all equal, wait errors (per unit time or per unit distance traveled during moving periods) are one-tenth of the gate failure rate, and moving a qubit over a unit distance is as noisy as a gate operation (corresponding to a scenario, say, in which moving over unit distance requires an actual swap gate execution). We have also optimized τ to be $\tau=4$, that is, $d = \lceil r/\tau \rceil = 13$, which means that error correction is performed on qubits in transit

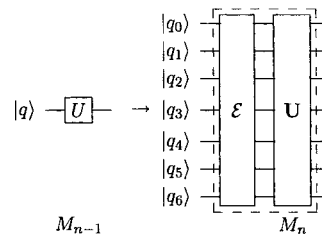


FIG. 11. The replacement rule for a one-qubit gate location U or a wait location. The dashed box represents a 1-rectangle. \mathcal{E} represents the error-correction procedure. \mathbf{U} represents the local fault-tolerant implementation of U . Note that in each figure, a qubit in M_{n-1} is encoded as $m=7$ qubits in M_n .

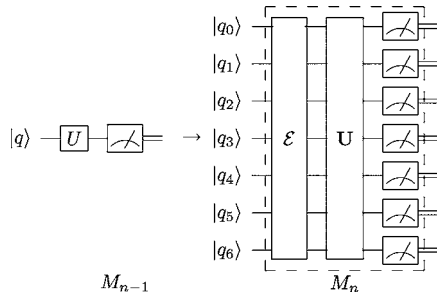


FIG. 12. The replacement rule for a one-qubit gate U followed by a measurement.

once every 13 units of distance moved (13 swap gates, say).

As Fig. 8 shows, for these conditions the threshold (we plot the γ_2 threshold value) decreases strongly with r ; the dependence is very close to $\gamma_2^{\text{thresh}} \propto 1/r$, confirming the analysis in Sec. III B. Note, however, that the findings are more optimistic here than the analytical lower bound in Sec. III B, that is, we see that $\gamma_2^{\text{thresh,loc}} \approx \gamma_2^{\text{thresh,nonloc}} \times c/r$ for some constant c which is a bit larger than 1. For a scale parameter $r=20$, which could well be a reasonable number, we get $\gamma_2^{\text{thresh}} = 0.73 \times 10^{-4}$, nearly an order of magnitude below the numbers typical in the nonlocal model, shown in Fig. 7. We have plotted these results in the high noise limit, but we have found similar behavior when the noise during transit is not very high, as seen in the dependence on r in Fig. 10 for small ϵ .

Figure 9 shows the result of varying τ for the failure probability choices of Fig. 8, with fixed $r=50$. We do this by choosing a τ that minimizes the threshold probability. After that we fix τ to be the optimal value, that is, we do not adjust τ at each level of concatenation. While the threshold value is not a very strong function of τ , it is clearly optimal for $\tau=4$. In more general studies in which we vary the initial values for γ and r , we do not find a simple relation between the optimal τ and these parameters.

This result was initially surprising to us, since it says that it is optimal to allow the moving qubits to become about 13 times noisier than the qubits involved in gate operations before they are error-corrected. The explanation for this seems to be that since qubits in motion do not have a chance of spreading error to other data qubits, allowing them to get noisier is not dangerous, and is actually desirable given the

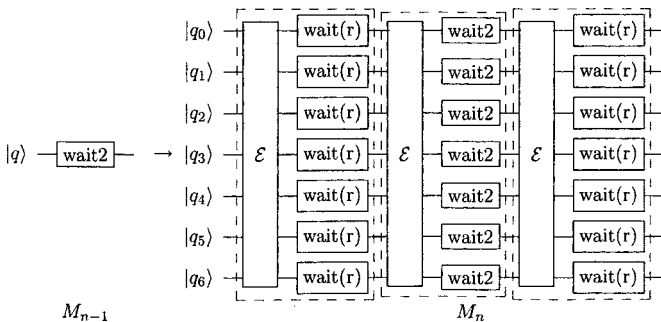


FIG. 13. The replacement rule for a wait2 (also called w_2) location acting in parallel with a two-qubit gate. The replacement circuit contains three elementary 1-rectangles.

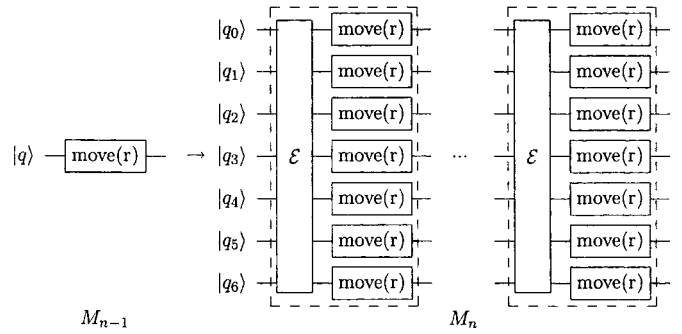


FIG. 14. The replacement rule for a $\text{move}(r)$ gate. The replacement circuit contains r elementary 1-rectangles.

level of errors introduced by the error-correction step itself. Of course, before they couple to other qubits we perform an error-correcting step in order to get rid of the accumulation of errors. A similar choice of less frequent error correction may be advantageous for a qubit that undergoes a few one-qubit and wait locations in succession. In such a case, errors do not spread to other blocks during these procedures and we finish the sequence by an error-correcting step as in the qubits in the transit case.

Finally, Fig. 10 shows the result of varying between noiseless moving and high-noise moving scenarios. This is captured by varying the parameter ϵ in the setting $\gamma_{md} = \epsilon r / \tau \times \gamma_2$. The choice for γ_{md} reflects the idea that the failure rates for qubits that are waiting during a move step should depend only on the distance moved (and, therefore, the time waiting during each elementary move step). $\epsilon=1$ is exactly the scenario explored in Figs. 8 and 9. $\epsilon=0$ corresponds to free moving, in which the qubit can be converted into some noiseless flying form for transportation; a rather artificial feature of this limit is that waiting is then noisier than moving. In Fig. 10, the other parameters are initially set as $\gamma_1 = \gamma_2 = \gamma_m = \gamma_p$, $\gamma_{w1} = \gamma_{w2} = 0.1 \times \gamma_2$, and $\gamma_{wd} = 0.1 \times r / \tau \times \gamma_2$.

It is evident from this that the error threshold is a weaker function of the moving failure rate ϵ than it is of the scale parameter r . When $\epsilon \rightarrow 0$, the waiting during moving is more error-prone than the moving itself and this waiting should be the main cause of the $1/r$ behavior in this limit. In other words, it is the scale-up of the circuit with every level of concatenation and the additional waiting this causes, i.e., a

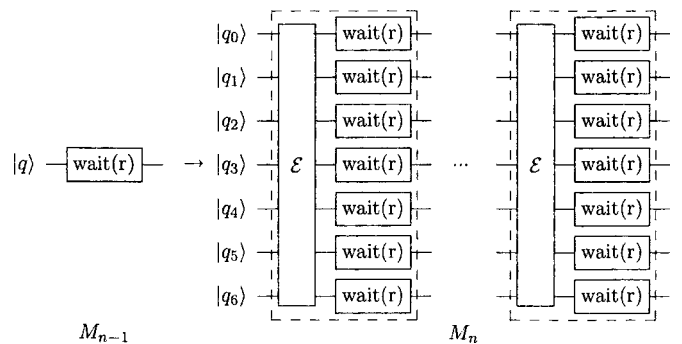


FIG. 15. The replacement rule for a $\text{wait}(r)$ gate. The replacement circuit contains r elementary 1-rectangles.

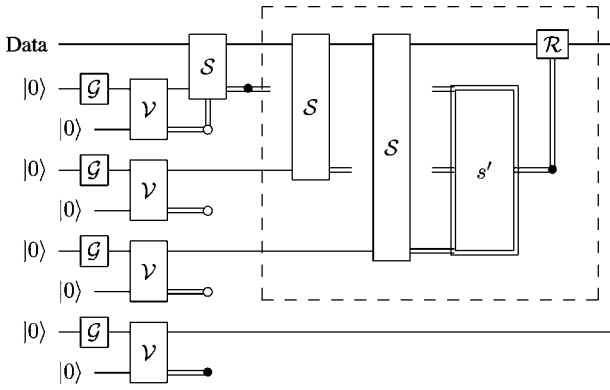


FIG. 16. The Steane X -error-correction protocol, \mathcal{X} [5]. The black circle represents control on a nonzero result. A white circle represents control on a zero result. s' represents a classical procedure to check if s' of the s syndromes agrees. The dashed box procedure is applied only if the controlling syndrome is not zero. There are n_{rep} prepared ancilla blocks. Each line represents seven qubits. After \mathcal{V} , α “good” verification blocks remain. \mathcal{R} represents the recovery procedure.

wait(d) location gets replaced by r wait(d) locations, which is the dominant reason why the threshold is lower than in the nonlocal model.

On the other hand, the “weak” dependence on ϵ seems to indicate that repeated error correction during moving is able to maintain acceptable fidelity for the moved qubits even in the face of moving errors.

This gives some new hope for schemes, such as those involving spins in semiconductors or Josephson junctions, in which qubit moving is inherently as difficult as gate operations. We know that in such a high failure-rate regime, entanglement distribution followed by purification and then teleportation can be a more effective way of moving qubits [6,7,17]. The rather strong sensitivity to r that we find (Fig. 8) suggests that if such strategies are employed, they should best be used in a way which does not increase the number of ancillas needed, and hence the scale parameter, too much.

Our numerics of course add a note of caution to this optimism: although the ϵ dependence we find is not too severe, over most of the range of the plot in Fig. 10, the actual

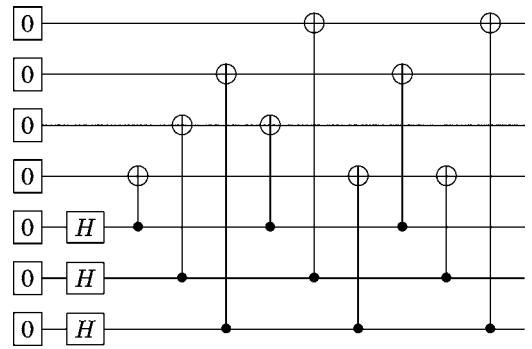


FIG. 17. The \mathcal{G} network for X or Z -error correction [3]. The network can be executed in five time steps. It produces the encoded $|0\rangle$ state. The boxed zero represents preparation of a $|0\rangle$ state.

values of the fault-tolerance threshold failure rate are well below 10^{-4} , in a range that is presently far beyond the capability of any quantum computer prototype in the laboratory.

VIII. OUTLOOK

We see at least two extensions of this direction of research. One is to indeed make the error-correction routine local, assuming some mechanism for short-distance transportation and a spatial layout of the qubits. We could then redo our local analysis, possibly with some more lengthy analysis of the failure probability that includes more details, in order to get a full estimate of the change in threshold due to locality. Secondly, one needs to consider where all the additional error correction in transit and moving will take place and has to design a layout for this. Given this layout, there may be modifications to the replacement rules in order to reflect the real architecture.

ACKNOWLEDGMENTS

Our quantum circuit diagrams were made using the Q-circuit LATEX macro package by Steve Flammia and Bryan Eastin. Krysta Svore acknowledges support by the NPSC. Barbara Terhal and David DiVincenzo acknowledge support by the NSA and the ARDA through ARO Contracts No.

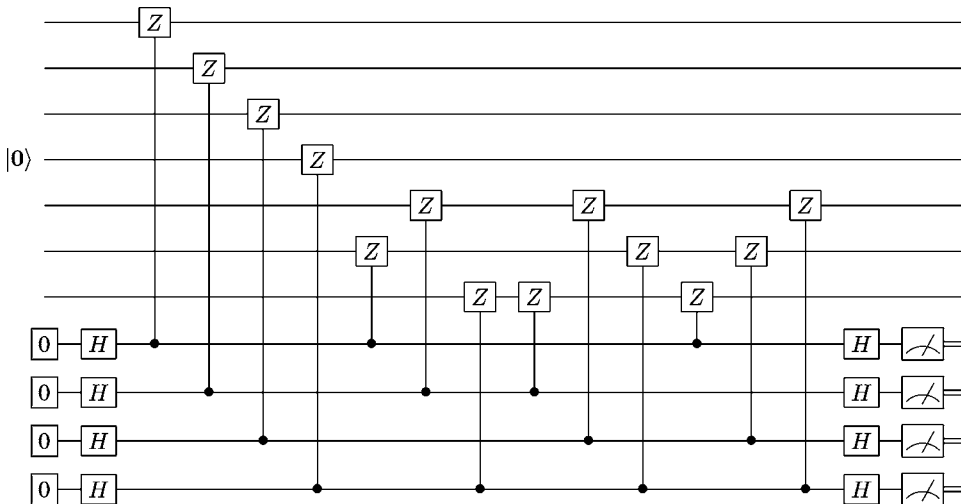


FIG. 18. The \mathcal{V} network [3,14], executable in six time steps. The boxed zero represents preparation of the $|0\rangle$ state. The state $|0\rangle$ is the seven-qubit encoded $|0\rangle$ state. If each measurement output is 0, then the ancilla block is deemed “good,” that is, it has been checked for X errors. The network is the same for the Z -error-correction procedure.

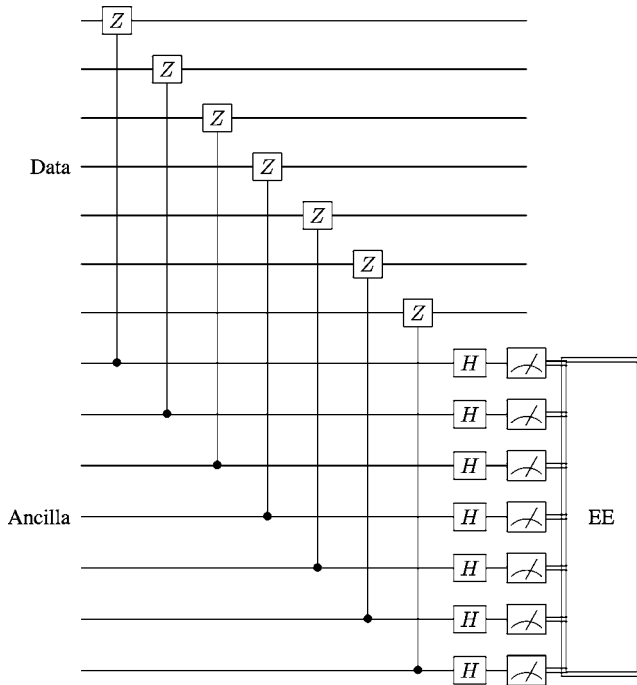


FIG. 19. The syndrome network \mathcal{S} for X -error correction [3]. This network can be executed in three time steps. Here EE represents classical error extraction. The network \mathcal{S} for Z -error correction uses C^X gates in place of C^Z gates, with the ancillas acting as control and the data as target qubits.

DAAD19-01-C-0056 and No. W911NF-04-C-0098.

APPENDIX: A REPLACEMENT RULES

The replacement rules are shown in Figs. 11–15.

APPENDIX B: DEFINITIONS OF n -RECTANGLES, BLOCKS, AND SPARSENESS

(i) A set of qubits in M_n is called an s -block if they originate from one qubit in M_{n-s} . An s -rectangle in M_n is a set of locations that originates from one location in M_{n-s} . An

TABLE VII. Number of locations of each type (1, 2, $w1$, $w2$, $1m$, or p) in individual routines \mathcal{G} , \mathcal{V} , \mathcal{S} and the recovery gates \mathcal{R} . The $w1$ and $w2$ locations combined are simply called w locations in the nonlocal analysis.

	1	2	$w1$	$w2$	$1m$	p
\mathcal{S}	0	7	14 (on data)	0	7	0
\mathcal{G}	3	9	4	3	0	7
\mathcal{V}	4	13	14	15+3	4	4
\mathcal{R}	1	0	6	0	0	0

s -working period is the time interval in M_n which corresponds to one time step in M_{n-s} .

(ii) Let B be a set of n -blocks in the computation M_n . An (n, k) -sparse set of qubits A in B is a set of qubits in which for every n -block in B , there are at most k $(n-1)$ -blocks such that the set A in this block is not $(n-1, k)$ -sparse. A $(0, k)$ -sparse set of qubits is an empty set of qubits.

(iii) A set of locations in an n -rectangle is (n, k) -sparse when there are at most k $(n-1)$ -rectangles such that the set is not $(n-1, k)$ -sparse in that $(n-1)$ -rectangle. A $(0, k)$ -sparse set of locations in a 0-rectangle is an empty set. A fault-path in M_n is (n, k) -sparse if in each n -rectangle, the set of faulty locations is (n, k) -sparse.

(iv) A computation code C has spread t if one fault occurring in a particular 1-working period affects at most t qubits in each 1-block, i.e., causes at most t errors in each 1-block in that particular working period.

APPENDIX C: ERROR-CORRECTING USING THE $[[7,1,3]]$ CODE

Figures 16–19 show the error-correction protocols.

APPENDIX D: GATE COUNTS

We calculate the number of locations in the circuits \mathcal{G} , \mathcal{V} , \mathcal{S} , and \mathcal{R} (see Table VII) for the recovery gate (see Figs. 17–19). Note that when recovery takes place, a one-qubit gate is executed on the data. We denote these numbers as $N(i \in \mathcal{G})$, etc.

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- [18] It is understood here and elsewhere that transportation of qu-

bits does not necessarily mean transportation of the physical embodiment of the qubit, but transport of the logical state of the qubit as in quantum teleportation.

[19] Of course, for a single level of concatenation, if M_0 is two-dimensional, we could put the ancillary qubits in the plane orthogonal to the two-dimensional data plane, so that transver-

sal two-qubit gates are between nearest-neighbor data blocks.

If we concatenate further, however, we run out of dimensions.

[20] If all failure probabilities were the same, and stayed the same after concatenation (this is what we assume in the analytical estimate in Sec. III), it is correct that one level of concatenation is enough to obtain the threshold.