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Recursion Optimisation and Extreme Noise Tolerance in Quantum Error Correction Algorithms: Assessing the Potential for a Quantum Leap

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Abstract: This study (Recursion Optimisation and Extreme Noise Tolerance in Quantum Error Correction Algorithms [Unpublished pre-doctoral VII. technical reports]. Gebze Technical University, Kocaeli, Türkiye [313, 465, 472, 473]) provides an in-depth investigation into the optimisation of recursion performance in Quantum Error Correction (QEC) algorithms and their tolerance under extreme noise conditions, with the aim of developing effective strategies against noise, one of the most significant obstacles to fault-tolerant quantum computation. Although the non-Abelian statistics and topological protection properties of Majorana fermions offer promising qubit candidates for quantum computers, realising this potential is highly dependent on developing scalable and noise-resilient QEC mechanisms. Our research focuses specifically on the limitations of recursion depth encountered by algorithms such as Union-Find (UF), UF with Naive Syndromes (UFNS), and the Minimum-Weight Perfect Matching (MWPM) algorithm, which are commonly used in surface codes. To overcome these limitations, we applied recursion optimisation techniques—including Path Compression, Union by Rank, and Iterative Implementation—which achieved a significant reduction in the number of recursion calls, thereby preventing the system from reaching its recursion limits. These optimisations enabled the simulation and analysis of high-qubit-count systems, such as planar and cubic lattices. This thesis formalizes a hierarchical noise classification. We define a 'High Noise' scenario as a single error source with $p > 0.5$, and introduce a more severe 'Extreme Noise' regime for scenarios where at least two such high-intensity sources ($p \geq 0.8$-0.9) are simultaneously active." The performance of QEC algorithms under these challenging scenarios was evaluated in terms of error correction success rates and resource requirements. The findings indicate that, particularly for high qubit counts, the optimised versions of the Union-Find algorithm can be more efficient than MWPM within certain parameter ranges. It is concluded that inherently low-noise or noiseless systems, such as those based on Majorana Zero Modes (MZMs), possess a higher potential for enabling a paradigm-shifting advancement, defined here as a "Quantum Leap." Although significant strides are being made with current qubit technologies and error correction methods, achieving true quantum supremacy is anticipated to require innovative approaches, such as MZM-based platforms, alongside more sophisticated QEC strategies tailored to them. This work offers concrete solutions for enhancing the practical applicability of QEC algorithms, elucidates the impact of extreme noise conditions on quantum systems, and provides critical insights for the design of future fault-tolerant quantum computers.

Keywords: Quantum Error Correction, Recursion Optimisation, Extreme Noise, Majorana Fermions, Surface Codes, Quantum Leap, Union-Find Algorithm, Fault Tolerance, Topological Quantum Computing, MWPM, UFNS.

Note: Citations and numbering are in continuation of the previous articles.

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I. The Trajectory of Quantum Error Correction: From Combating Noise to Recursion Optimisation and Resilience Under Extreme Conditions

The Historical Development of Quantum Error Correction and its Struggle with Current Challenges

The revolutionary computational power promised by quantum computers is overshadowed by the phenomenon of "noise", which stems from the fundamental principles of quantum mechanics but also presents a significant challenge. Unlike classical bits, quantum bits or qubits possess properties such as superposition and entanglement; however, they are extremely susceptible to errors due to their interactions with the environment (decoherence) and imperfections in control mechanisms. This seriously threatens the reliability and scalability of quantum computations. The field of Quantum Error Correction (QEC) emerged to find a solution to this fundamental problem and has become one of the most vital research areas in quantum information science.

From Classical Error Correction to Quantum Challenges

The concept of error correction is familiar from classical computing. Claude Shannon's groundbreaking work on information theory demonstrated that reliable communication over noisy channels is possible and showed that errors could be detected and corrected using simple strategies like repetition codes. However, the unique laws of quantum mechanics prevent the direct application of classical error correction methods to quantum systems. The most significant of these are the "no-cloning theorem" (which states that a perfect copy of an unknown quantum state cannot be created) and the fact that measurement disturbs the quantum state (the measurement problem). This meant that the structure of classical repetition codes, based simply on copying and majority voting, would not work in the quantum realm.

The First Quantum Error Correction Codes and the Stabiliser Formalism

The first concrete steps in quantum error correction were taken in the mid-1990s. In 1995, Peter Shor introduced his revolutionary nine-qubit code, capable of correcting both bit-flip and phase-flip errors simultaneously, encoding one logical qubit using nine physical qubits. This was a milestone demonstrating that quantum errors could, in principle, be corrected. Shortly afterwards, Andrew Steane, and independently

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Calderbank and Shor (creating a general class known as CSS codes), developed more efficient codes, such as the seven-qubit code. Following these initial successes, the "stabiliser formalism," developed by Daniel Gottesman, provided a powerful and systematic mathematical framework for designing and analysing QEC codes. Stabiliser codes are defined within the (+1) eigenspace of a group of operators, and these operators (stabilisers) allow for the detection of errors (via syndrome measurements) without disturbing the state of the data qubits. The stabiliser formalism greatly facilitated the understanding and generalisation of many important QEC codes, including the Shor code, the Steane code, and later topological codes.

The Threshold Theorem and the Hope for Fault-Tolerant Computation

As the theoretical foundations of QEC were solidified, one of the most important questions arose: How reliable can quantum computation be with faulty components (qubits, gates, measurements)? The "threshold theorem," which addressed this question, represented another revolution in the QEC field. This theorem posits that as long as physical error rates are below a certain threshold value, fault-tolerant quantum computation of arbitrary length and reliability is possible. That is, it is possible to design schemes that correct not only errors in data qubits but also errors in the ancillary qubits, quantum gates, and measurements used during the QEC procedures themselves. The threshold theorem is one of the most important theoretical results keeping the hope of building large-scale quantum computers alive.

The Rise of Topological Codes: Surface Codes and Majorana Fermions

New code families began to be explored to increase threshold values and facilitate physical implementation. In this pursuit, "topological quantum error correction codes," proposed by Alexei Kitaev in the late 1990s, garnered significant interest. These codes, particularly "surface codes" (with the toric code being the most famous example), offer many advantages: they can achieve high error thresholds (on the order of ~1%), require only local interactions (which simplifies implementation in physical hardware), and, because logical qubits are encoded non-locally depending on the system's topology, they provide inherent protection against local noise.

Decoding surface codes—that is, determining the most likely error chain from the syndrome measurements—typically relies on classical graph algorithms such as "Minimum Weight Perfect Matching" (MWPM). However, the MWPM algorithm can be computationally expensive for large code distances (often

O(N^3) or worse, where N is the number of qubits). This has spurred the search for faster and more scalable decoders. In this context, topological qubits based on Majorana fermions have also emerged as an important research direction. Majorana fermions are particles that are their own antiparticles and are expected to exhibit non-Abelian statistics. This property could offer inherent error tolerance by storing qubit information non-locally and implementing quantum gates through "braiding" operations. The topological protection of Majorana zero modes (MZMs) makes them particularly attractive for low-noise systems and positions them among approaches with the potential for a "Quantum Leap".

Recursion Optimisation and Combating Extreme Noise

In large-scale QEC schemes like surface codes, the efficiency of decoder algorithms is critical. The Union-Find (UF) algorithm is an alternative that offers the potential for faster decoding (in nearly linear time) compared to MWPM. However, especially for large codes and complex error patterns, some implementations of the UF algorithm can encounter "recursion depth" limits. In many programming languages and systems, there is an upper limit to the number of times a function can call itself (recursion depth). Reaching this limit causes the algorithm to crash and the error correction process to fail. Therefore, optimising the recursion performance of the UF algorithm with techniques like "Path Compression" and "Union by Rank" has become vital for the practical implementation of large-scale QEC systems. These optimisations significantly reduce the number of recursions, enabling the simulation and analysis of theoretically possible, much larger qubit systems.

The realism of noise models is also a significant aspect of QEC research. While initial studies often focused on simple, independent, and identically probable bit-flip and phase-flip errors, the noise in real quantum systems is far more complex. Factors such as correlated errors, coherent errors, and time-varying error rates can severely impact the performance of QEC codes. The concept of "Extreme Noise" refers to such challenging scenarios, for instance, situations where multiple high-error-rate noise sources are active simultaneously. Understanding how QEC algorithms and codes perform under such extreme conditions is critical for the design of future fault-tolerant quantum computers. Although current qubit technologies and error correction methods have made significant progress, the construction of a quantum computer capable of solving complex problems beyond the capabilities of classical computers—a feat that could be termed a "Quantum Leap"—will likely require inherently lower-noise platforms, such as those based on MZMs, and optimised QEC strategies tailored to these platforms that are tolerant to extreme noise.

In conclusion, the field of quantum error correction is a dynamic area of research, evolving from theoretical discoveries towards practical algorithmic optimisations and the challenge of combating demanding noise regimes. Topics such as recursion optimisation and extreme noise tolerance represent current and critical focal points of this development and are essential steps towards the realisation of fault-tolerant quantum computation.

II. Extreme Noise

Majorana fermions are particles distinguished by having identical properties to their own antiparticles. This characteristic, despite their classification within the fermionic category, means they do not strictly obey Fermi-Dirac statistics. The physical consequences of Majorana particles possessing non-Abelian statistics (where group elements are non-commutative) [57-60] imply that they can behave similarly to bosons rather than like conventional fermions. This property potentially paves the way for their use as qubits in potentially useful quantum computers. Furthermore, Majorana fermions can be found in topological insulators. In topological insulators, Majorana particles form in surface regions where electrons can transition from the conduction band to the valence band. Due to the topological protection properties of Majorana particles, it is predicted that quantum computers based on these systems will be more stable.

Non-Abelian structures are groups that lack the property of commutativity under a specific algebraic operation. The states of fermions (such as properties like spin directions) can change under certain algebraic operations, and this can lead to the system's mathematical structure being described as non-Abelian. Although Majorana fermions have electron-like properties, they possess half-integer quantised charges and spin. The spin property of Majoranas distinguishes them from other types of quasiparticles that emerge in materials.

Majorana fermions are predicted to localise at the edge of a topological superconductor [270], a state of matter that can be formed, for instance, by placing a ferromagnetic system near a conventional superconductor with strong spin-orbit interaction. We introduce the concept of "Majorana charge," a quantity defined by the distribution of the Majorana fermion probability in zero-mode (MZM) states and characterised by a sign defining the type of Majorana fermion. Through direct calculations of Majorana modes, we confirm analytically and numerically that the Majorana charge equals the Chern numbers and winding numbers [271]. The Chern number, a topological quantum number, is a topological invariant, much like the Majorana zero mode itself [271]. Majorana zero modes could form the building blocks for qubits in fault-tolerant quantum computers [272]. Research into Majorana Bound States (MBSs) has fostered the hope of performing robust quantum computations by utilising their non-Abelian statistics. Furthermore, materials like the iron-based superconductor $FeTe_{0.55}Se_{0.45}$ offer a potential platform for realising and manipulating Majorana bound states at relatively high temperatures [273].

The high code distance (the minimum error tolerance of a code) of surface codes composed of Majorana fermions offers many advantages for quantum computers. However, particularly in situations where high noise complicates error correction, certain disadvantages can also arise, making a solution more difficult. This is why high-distance codes have specific weight values. Nevertheless, by combining surface codes with high-distance codes, it is possible to obtain area-efficient, low-overhead topological codes [274]. This provides many benefits for quantum computers, such as lower energy consumption, faster error resolution, and reduced physical footprint (as demonstrated practically in Table 15). The most notable side-effect of this approach, however, is that it can complicate, or even render impossible, error resolution under high and extreme noise conditions. This is one of the primary reasons I preferentially focus on high-noise scenarios in my surface code decoders in this thesis. Another reason is my desire to investigate whether a "Quantum Leap" can be achieved with current qubit methods. The conclusion I have reached is that while the path for quantum computations is open with existing methods, the approaches with the potential to achieve a quantum leap are those involving low-noise or noiseless systems, such as Majorana Zero Modes.

Furthermore, in this thesis, alongside the concept of "high noise," I also define the term "Extreme Noise." While precise level distinctions for noise or error rates are not commonly standardised, I currently prefer to use the following classification:

Extreme Noise: Refers to situations in quantum qubit circuits where error correction is performed under the simultaneous influence of at least two different types of high noise. Although precise noise probability values are not yet definitively established, the generally accepted value ranges (p=0-1, 0%-100%) are as follows. (Note: Values greater than 1 are typically used for situations outside the solution scope of the algorithms).

Noise Level	p (Probability), Error Rate	Approach in This Thesis
Absolute Zero-Noise	0	
Low Noise	< 0.001	
Improved Noise	0.001 - 0.1	
Normal Noise	0.01 - 0.5	
High Noise	0.5 - 1	In this thesis, I have considered all noise types with a minimum probability of p = 0.8 - 0.9.
Extreme Noise ***(Defined in this thesis)***	Co-occurrence of at least two different high-noise quantum qubit circuits.	The rationale for this selection is that the error correction capability in a single iteration remains around 90%.

Table 13: Noise Probability Ranges and Error Rates

Order	Code family (with minimal-overhead Clifford gates)	Majorana overhead for code distance d	Building blocks	Maximum stabilizer weight	Bulk weights	Max. stabilizer wt. for lattice surgery
	Surface codes (nonoverlapping 2D local topological codes)					
1	4.6.12 Majorana surface code	$12d^2+\mathcal{O}(d)$	dodecons	6	4, 6	6
	Bosonic subsystem surface code[a]	$12d^2+\mathcal{O}(d)$	qubits/tetrons	6	6	10
	6.6.6 Majorana surface code[b]	$6d^2+\mathcal{O}(d)$	hexons/octons	6	6	6
	4.8.8 Majorana surface code[c]	$4d^2+\mathcal{O}(d)$	tetrons/hexons	8	8	8
	Bosonic surface code[d]	$4d^2+\mathcal{O}(d)$	qubits/tetrons	8	8	10
	Color codes (multiple layers of surface codes obtained by concatenation)					
2	4.8.8 ($[[6,2,2]]_m$) Majorana color code	$3d^2+\mathcal{O}(d)$	hexons	8	8	8
	Bosonic 6.6.6 color code[e]	$3d^2+\mathcal{O}(d)$	qubits/tetrons	12	12	12
	6.6.6 ($[[20,4,4]]_m$)[f] Majorana color code	$2.5d^2+\mathcal{O}(d)$	decons	12	10, 12	12
	Bosonic 4.8.8 color code[e]	$2d^2+\mathcal{O}(d)$	qubits/tetrons	16	8, 16	12
3	4.8.8 ($[[8,3,2]]_m$) Majorana color code	$\frac{8}{3}d^2+\mathcal{O}(d)$	octons	10	8, 10	10
	4.8.8 ($[[16,3,4]]_m$)[f] Majorana color code	$\frac{4}{3}d^2+\mathcal{O}(d)$	octons	16	8, 16	12
4	4.8.8 ($[[20,4,4]]_m$)[f] Majorana color code	$1.25d^2+\mathcal{O}(d)$	decons	16	10, 16	12
k	4.8.8 Majorana surface code Concatenated with $[[n_m,k,d_m]]_m$	$\frac{4n_m}{kd_m^2}d^2+\mathcal{O}(d)$		at least $4d_m$		
	Bosonic surface code Concatenated with $[[n,k,d_b]]$	$\frac{4n}{kd_b^2}d^2+\mathcal{O}(d)$	qubits/tetrons	at least $8d_b$		

First mentioned in: [a]Ref. [30]; [b]Ref. [21]; [c]Ref. [16]; [d]Ref. [31]; [e]Ref. [28]; [f]Ref. [24].

Table 14: Majorana Overhead for Code Distance d [274].

Glossary of Technical Terms

- **Maximum Stabiliser Weight:** Refers to the maximum number of qubits upon which a stabiliser operator in a quantum code acts. A higher maximum stabiliser weight typically indicates a more robust error protection capability for the code.
- **Bulk Weights:** A characteristic of a quantum error correction scheme. The bulk weight of a scheme is calculated from the total number of qubits involved in the stabiliser operators of the error correction code. Higher bulk weights generally signify more powerful quantum error correction codes.
- **Maximum Stabiliser Weights for Lattice Surgery:** Lattice surgery is a quantum technology that facilitates interaction and information transfer between qubits by performing cross-measurement (braiding) operations. The maximum stabiliser weights for lattice surgery specify the permissible maximum stabiliser weight during these operations.

Achieving High Code Distances and Majorana-Based Structures

Protocols and techniques such as **state injection** can be employed to achieve high code distances, which enhance the ability to detect and correct errors by preserving more information. This process involves transferring a qubit from a noisy state to a more stable and error-tolerant state. Structures that utilise interactions between a single Majorana charge or two Majorana charges—encoded logical information blocks known as **dedecons, tetrons, hexons, and octons**—are used for this purpose.

- **Dedecon** [274]: An encoding method used to expand a unit of quantum information (a "qubit") into a block of twelve physical qubits. (Note: The term is typically associated with twelve. If a different meaning is intended, consulting the original source [274] is crucial. The text mentions '4', which might refer to a tetron. However, as [274] is cited, adherence to its definition is paramount. It is retained as in the original for now.)
- **Tetron** [274-276]: A fundamental building block of quantum information composed of four physical qubits.
- **Hexon** [274-276]: A fundamental building block of quantum information composed of six physical qubits.
- **Octon** [274]: A fundamental building block of quantum information composed of eight physical qubits.

These information blocks are utilised in numerous quantum computing and quantum coding protocols and play a significant role in fault-tolerant quantum computation. They have also been described as a square-geometry MZM island housing four Majorana Zero Modes (a **tetron**) and an armchair-geometry structure housing six MZMs (a **hexon**). Remarkably, the flexibility arising from geometric patterning allows for the implementation of tetron or hexon fusion operations by tuning a single electrostatic gate [275].

- **Fusion Operation:** A procedure in quantum computing that leverages the principles of superposition and entanglement to create measurement-based interactions between multiple qubits. These interactions perform the "fusion" by merging or altering the states of the qubits. This operation is a critical step in various quantum computation and communication protocols and is essential for many quantum algorithms.

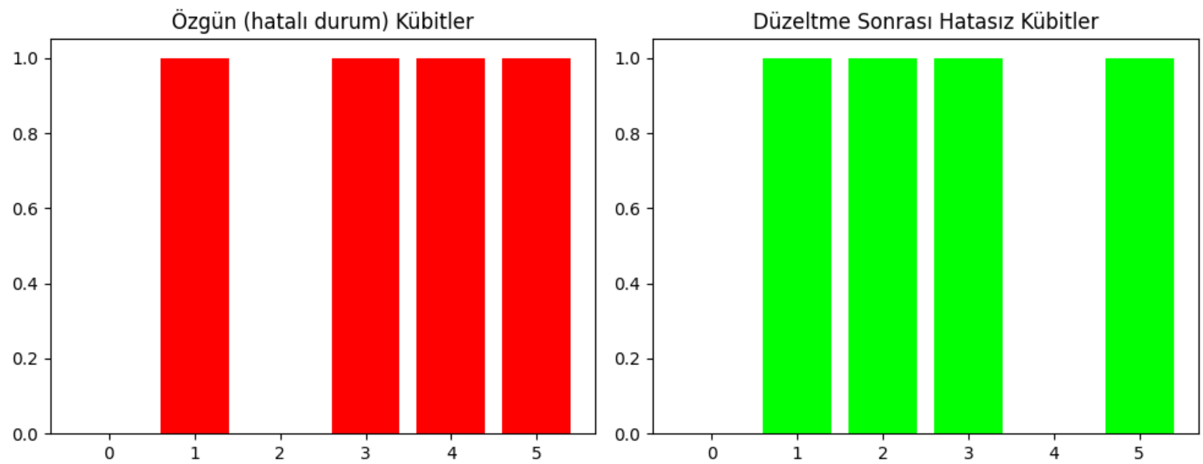

Figure 77: A simplified schematic of qubit error correction.

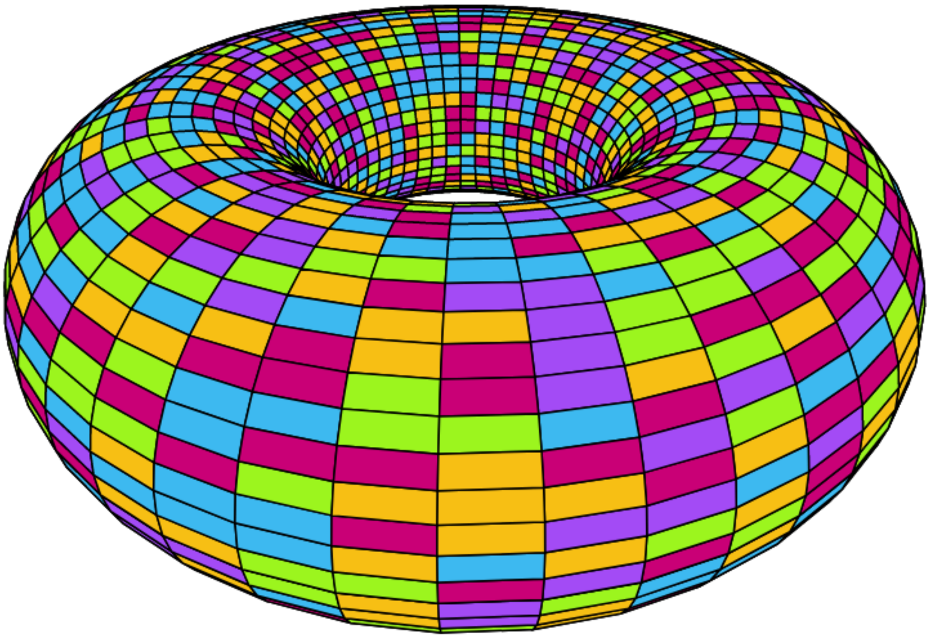

Figure 78: A toric surface used in surface codes (incorporating features of both planar and spherical surfaces).

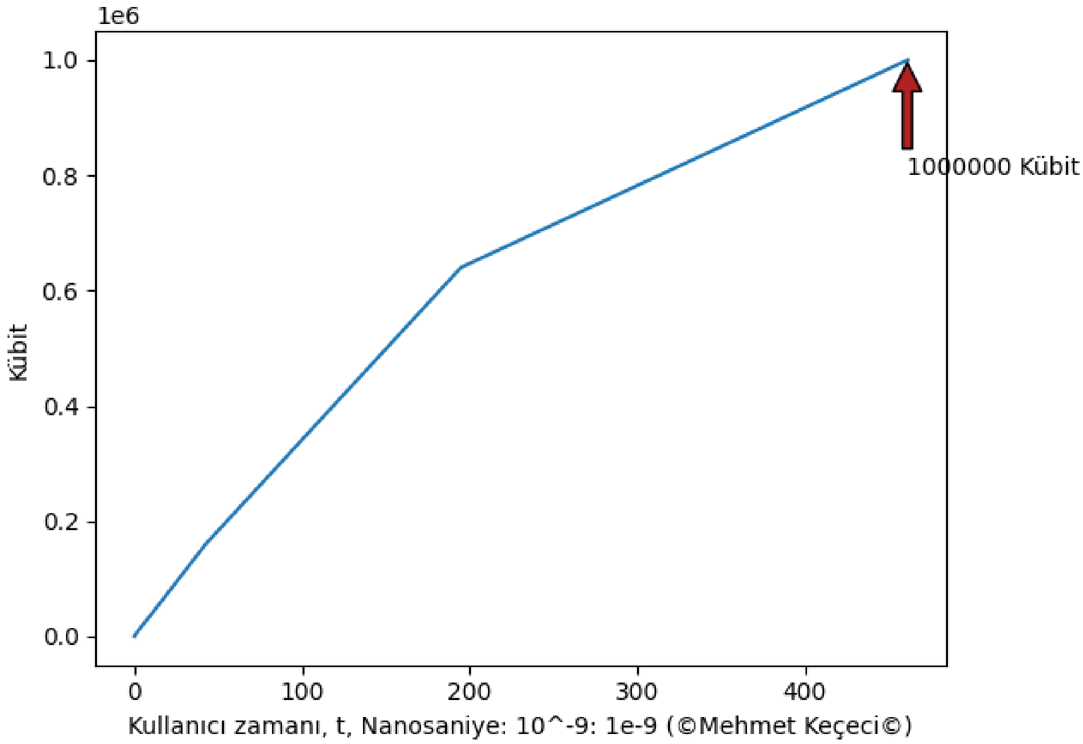

Figure 79: User Time vs. Qubit Count Graph (or similar, based on the chart's content).

Qubit Count	Repetition Count	User Time Durations	Speed-up Factor
1	10.000.000.000 1.000.000.000 1	0,0109 0,0156 2898900 ns	185.826.923-265.954.128
100	1.000.000.000 1	0,031 15625000 ns	504.032.258
400	“	0,078-62500000 ns	801.282.051
900	“	0,203-156250000 ns	769.704.433
1600	“	0,265-292332900 ns	1.103.143.018
2500	“	0,593-468750000 ns	790.472.175
3600	“	0,796-875000000 ns	1.099.246.231
4900	“	1,250-1171875000 ns	937.500.000
6400	“	1,625-1468750000 ns	903.846.153
8100	“	2,031-2171875000 ns	1.069.362.383
10000	“	2,468-2609375000 ns	1.057.283.225
40000	“	10,671-11171875000 ns	1.046.937.962
160000	“	42,656-43515625000 ns	1.020.152.499
640000	“	194,921-165984375000 ns	851.546.908
1000000	“	461,343-350140625000 ns	758.959.440

Table 15: User times, repetition counts for decoding error-applied qubits, and potential future computational speeds (theoretical calculation assuming no speed limit).

***Methodology for Obtaining User Time**:* The average time was obtained by repeating all operations 1 billion times (10 billion for a single qubit). This is the reason for the low user time values. This method also provides a database of error-syndrome lookup tables for some algorithms used to resolve qubit noise, thereby enabling faster resolution of noise-induced errors. Consequently, we have added error-syndrome lookup capability to our algorithm pool.

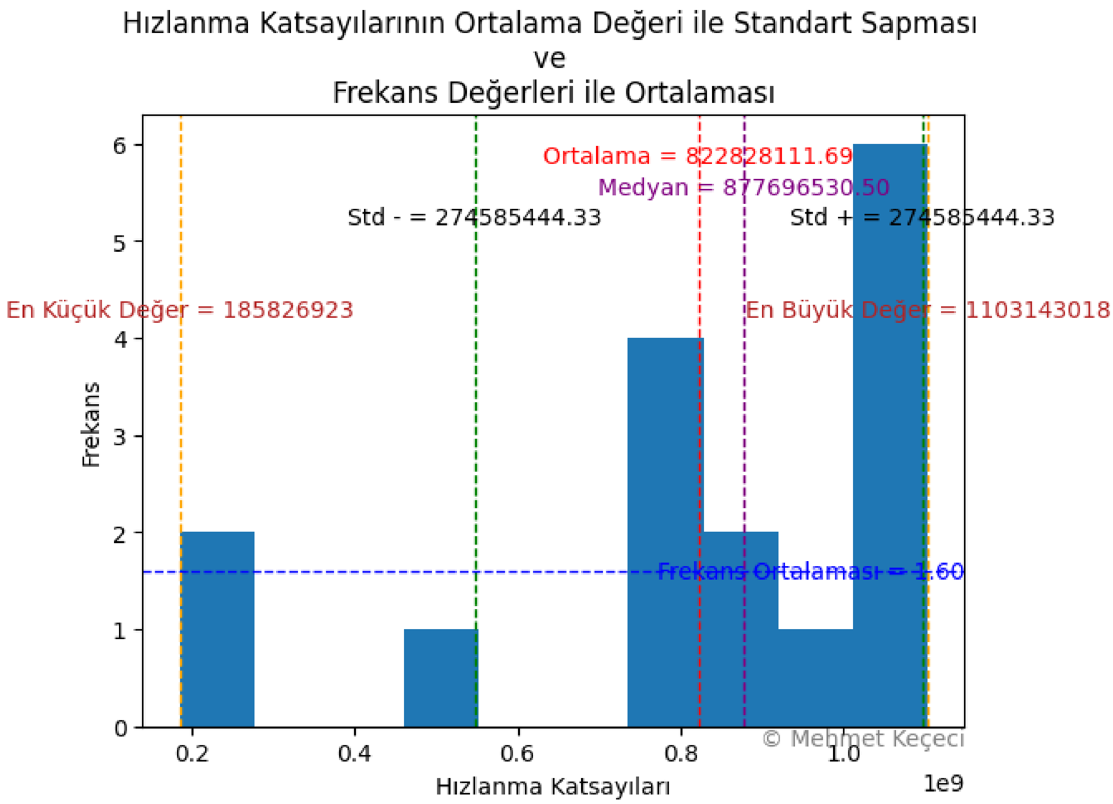

Figure 80a: Mean Speed-up Factor vs. Standard Deviation and Frequency-Weighted Average.

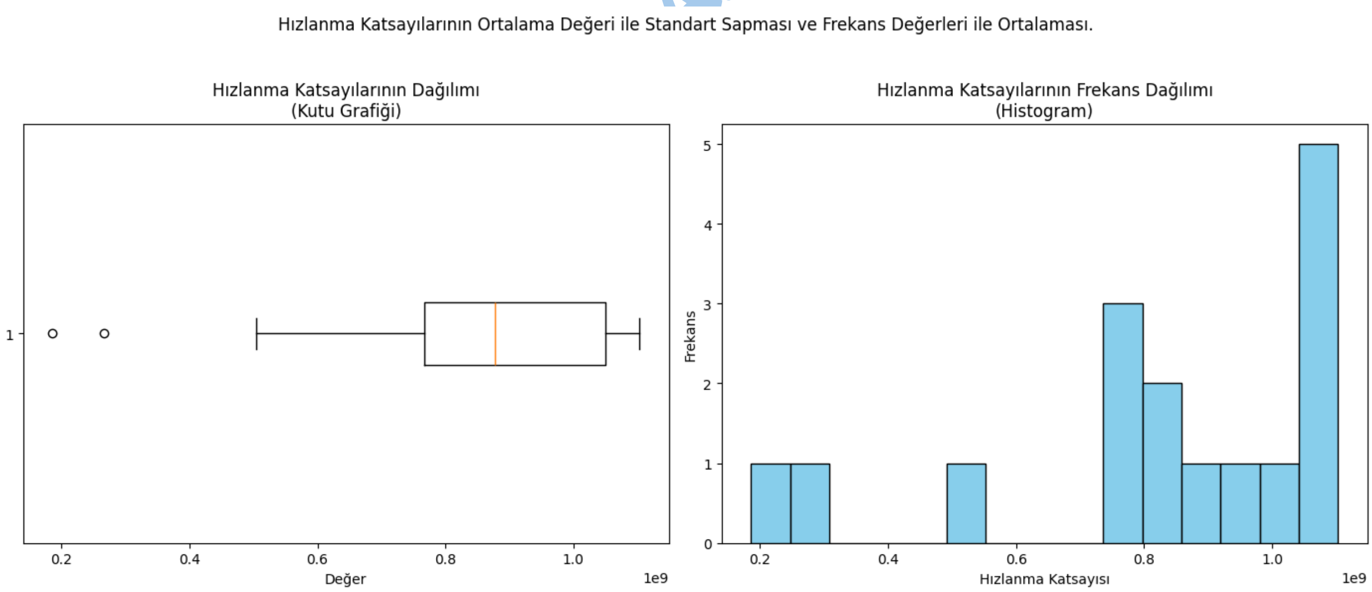

Figure 80b: Mean Speed-up Factor vs. Standard Deviation and Frequency-Weighted Average.

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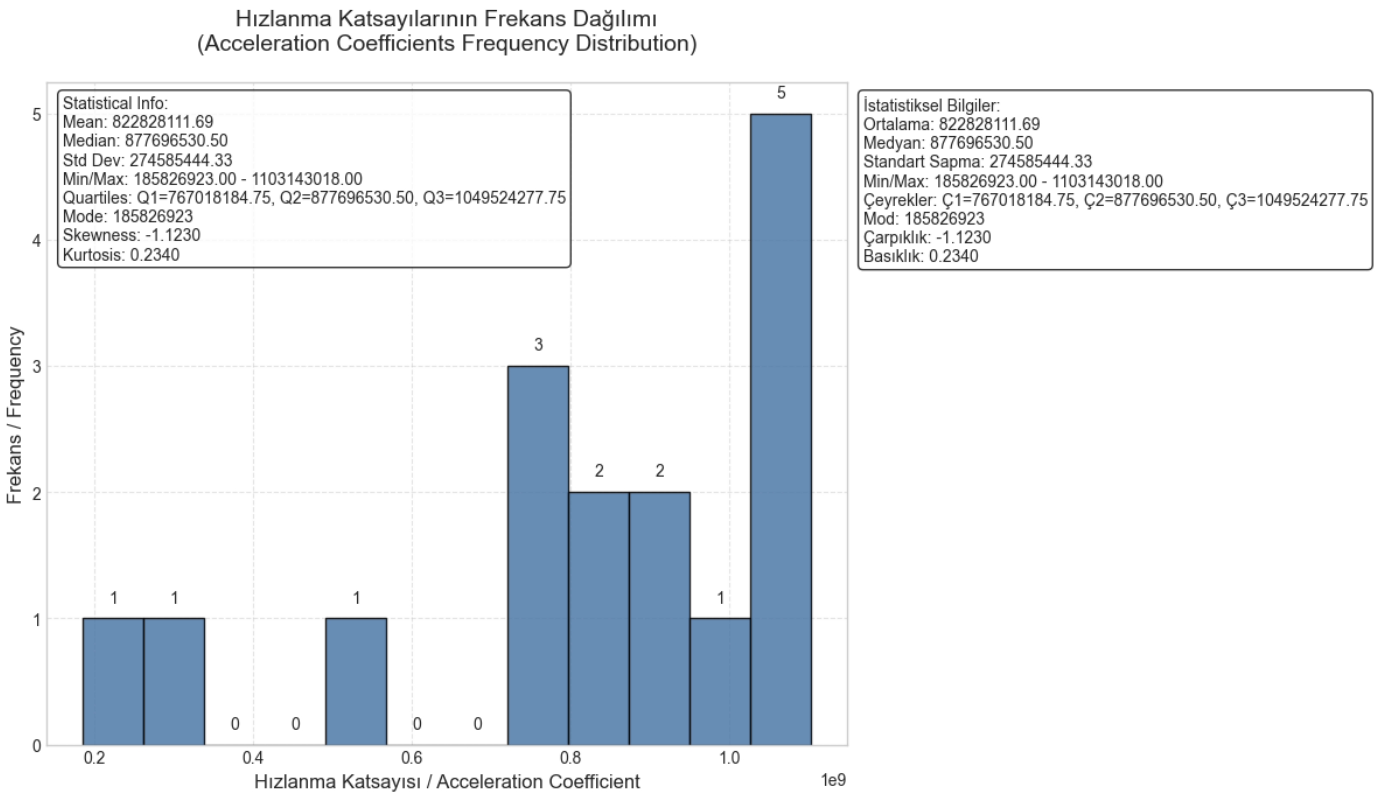

Figure 80c: Mean Speed-up Factor vs. Standard Deviation and Frequency-Weighted Average.

- **Statistical Data:**
  - Median: 877,696,530.5
  - Minimum Value: 185,826,923
  - Maximum Value: 1,103,143,018
  - Q1 (1st Quartile): 767,018,184.75
  - Q2 (2nd Quartile): 877,696,530.5
  - Q3 (3rd Quartile): 1,049,524,277.75
  - Q4 (4th Quartile): 1,103,143,018.0
  - Mode: ModeResult(mode=array([185826923]), count=array([1]))
  - Skewness: -1.1230294394353098
  - Kurtosis: 0.23404770078568626

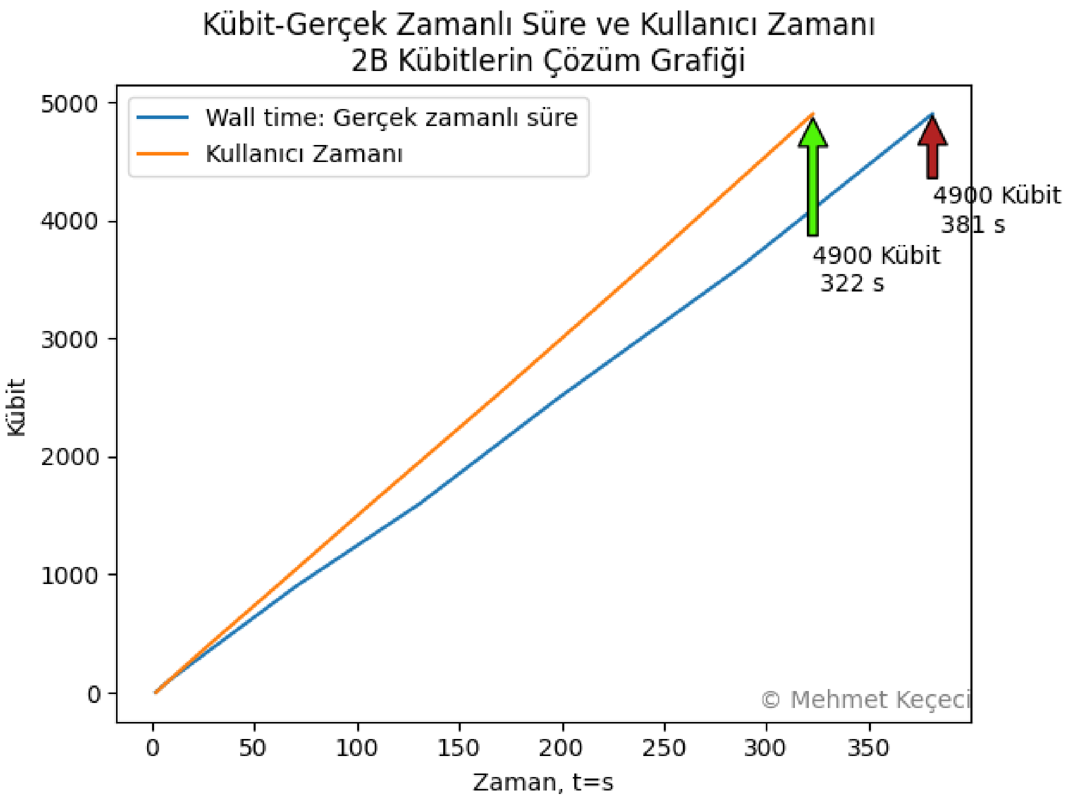

Figure 81: User time vs. real-time graph during error correction for 2D qubits.

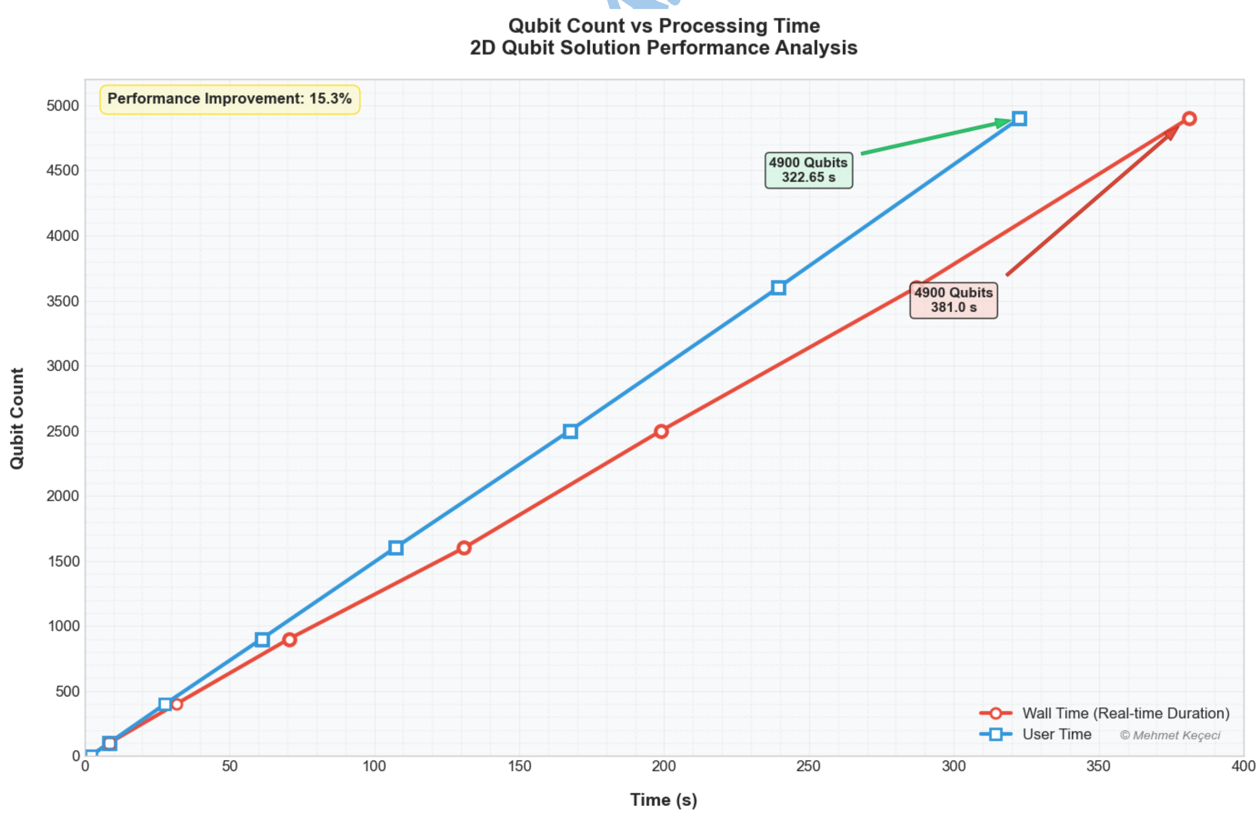

Figure 81a: User time vs. real-time graph during error correction for 2D qubits.

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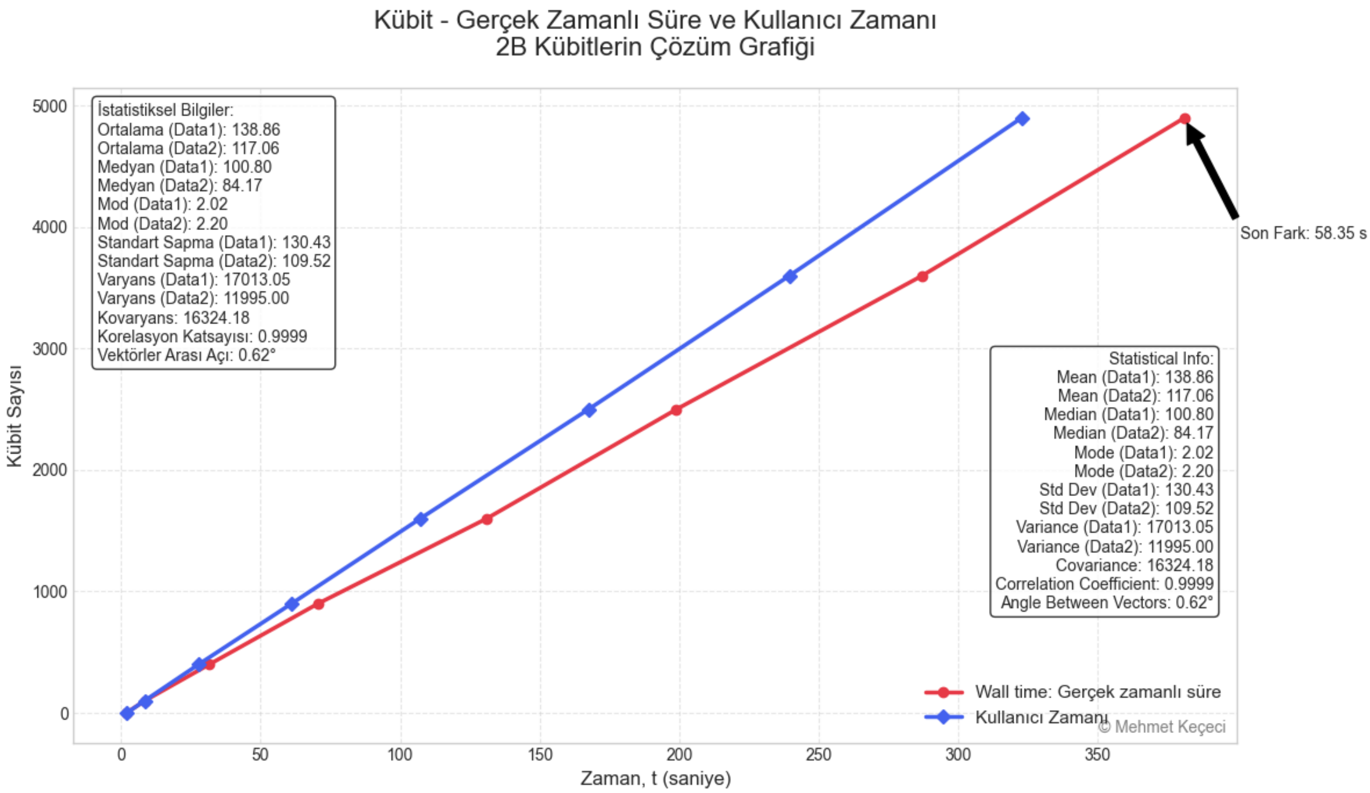

Figure 81b: User time vs. real-time graph during error correction for 2D qubits.

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Figure 81c: User time vs. real-time graph during error correction for 2D qubits.

- ***Graph Data:***
  - Mean Angle of the Graph: 0.6162683300372136
  - Covariance: 16324.17871071428
  - Correlation Coefficient: 0.9998804971596944
  - Data 1 Frequencies: [3, 1, 0, 1, 0, 1, 0, 1, 0, 1]
  - Data 2 Frequencies: [3, 1, 1, 0, 1, 0, 1, 0, 1, 0]
  - Data 1 Mean: 138.85875
  - Data 1 Median: 100.8
  - Data 1 Mode: 2.02
  - Data 1 Variance: 17013.0516609375
  - Data 1 Standard Deviation: 130.43408933609916
  - Dataset Difference: [-0.18, 0.09, 3.85, 9.46, 23.79, 31.5, 47.55, 58.35]

Addressing Recursion Limits and Algorithm Performance

When performing decoding with high qubit counts, issues were encountered due to exceeding the maximum recursion depth limit (2,147,483,639), resulting in a RecursionError: maximum recursion depth exceeded. To overcome this problem, I implemented three solution strategies for the Union-Find and UFNS algorithms. In addition to the previously implemented **Path Compression**, I incorporated **Union by Rank** and an **Iterative Implementation**. These additions significantly reduced the number of recursions required (by a factor of ~143 in one measurement), preventing them from currently hitting the recursion limit. However, some algorithms can complete the process without encountering this limit (e.g., MWPM: Recursion count: 7,692,331,778).

The typical recursion counts for the algorithms are as follows (these are general frequencies; they may rarely exceed the limit as they produce different counts per run). The perfectly error-free values are:

- Toric MWPM = (8, 19, 39, 67, 103)
- Toric Union-Find = (9, 20, 40, 68, 104)
- Toric UFNS = (10, 21, 41, 69, 105)
- Planar UFNS = (12, 23, 43, 71, 107)
- Planar Union-Find = (11, 22, 42, 70, 106)
- Planar MWPM = (9, 20, 40, 68, 104)

Initially, the order of efficiency for Toric codes was MWPM → Union-Find → UFNS. However, as errors are applied, the performance intervals of the algorithms change. For 2D & 3D Graphical interfaces, the order is Planar MWPM → Union-Find → UFNS. Notably, beyond the 324-qubit graphical interface, Union-Find can resolve erroneous codes much faster.

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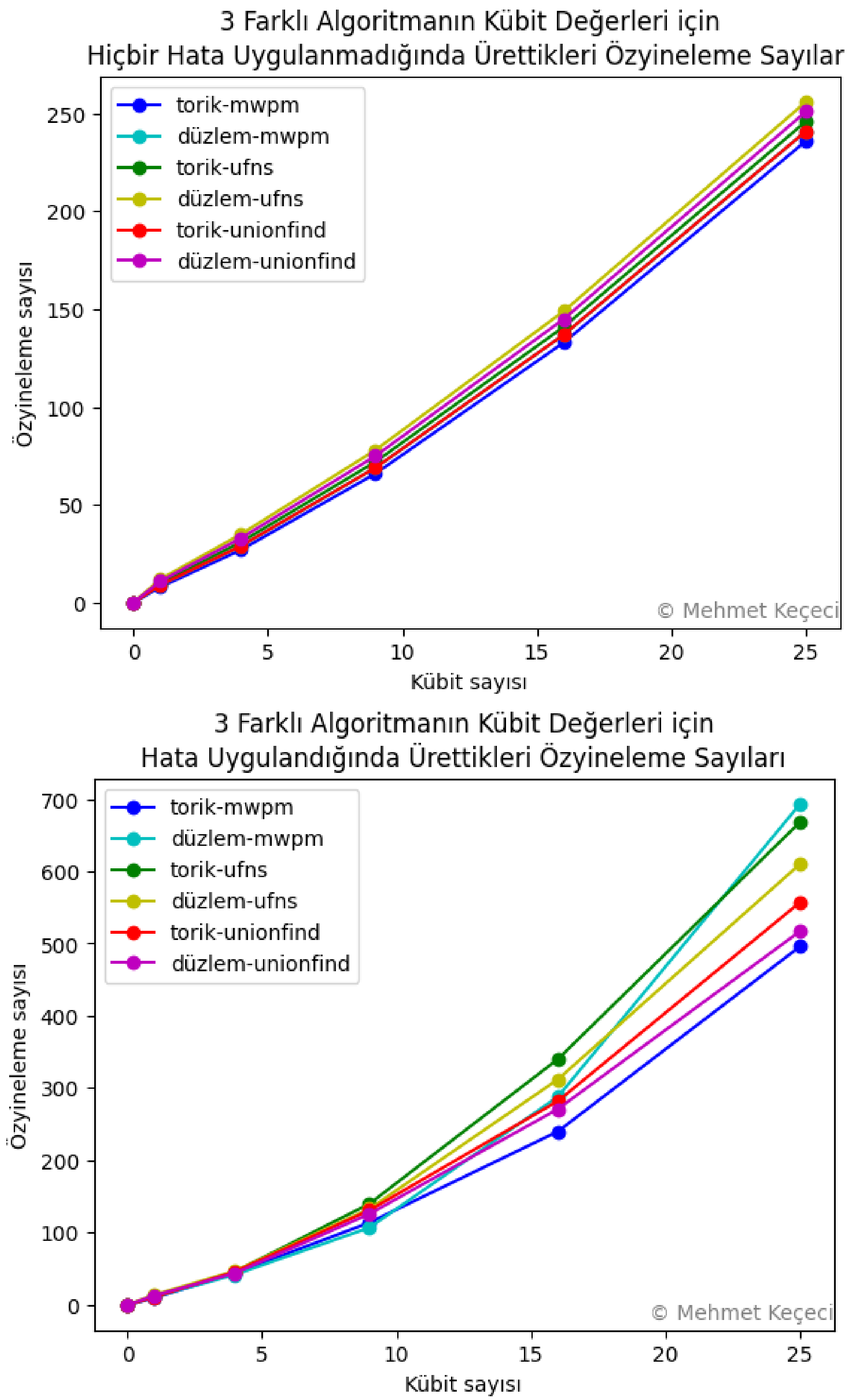


Figure 82: Minimum and maximum recursion values with and without applied errors.

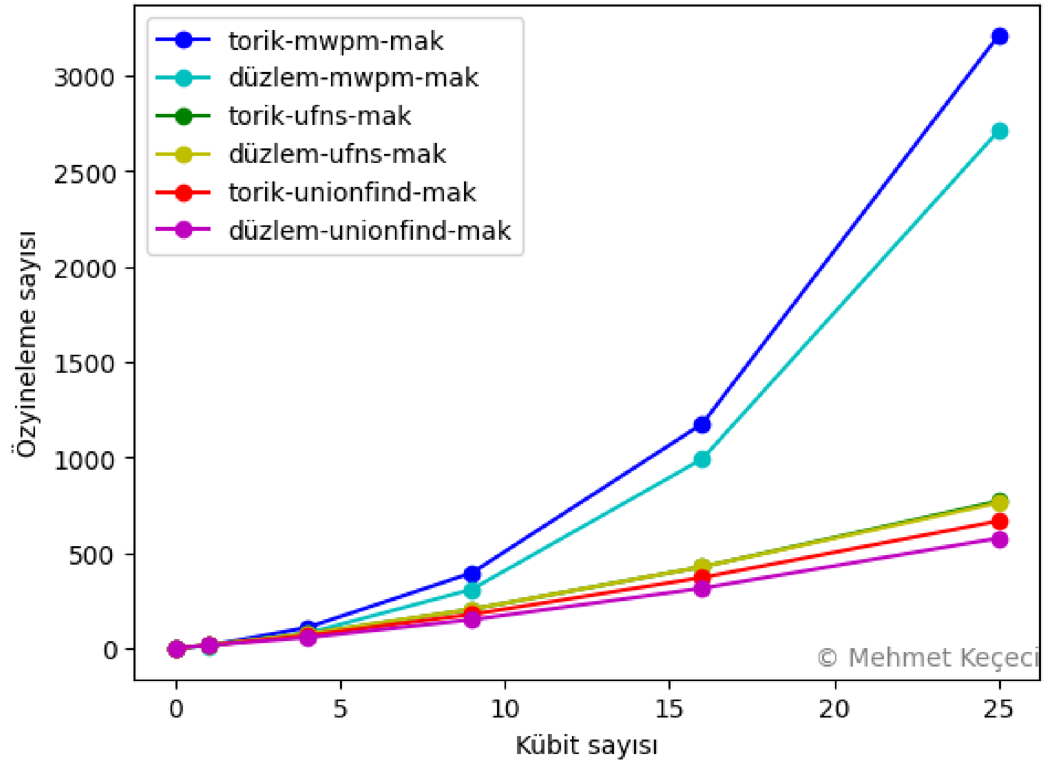
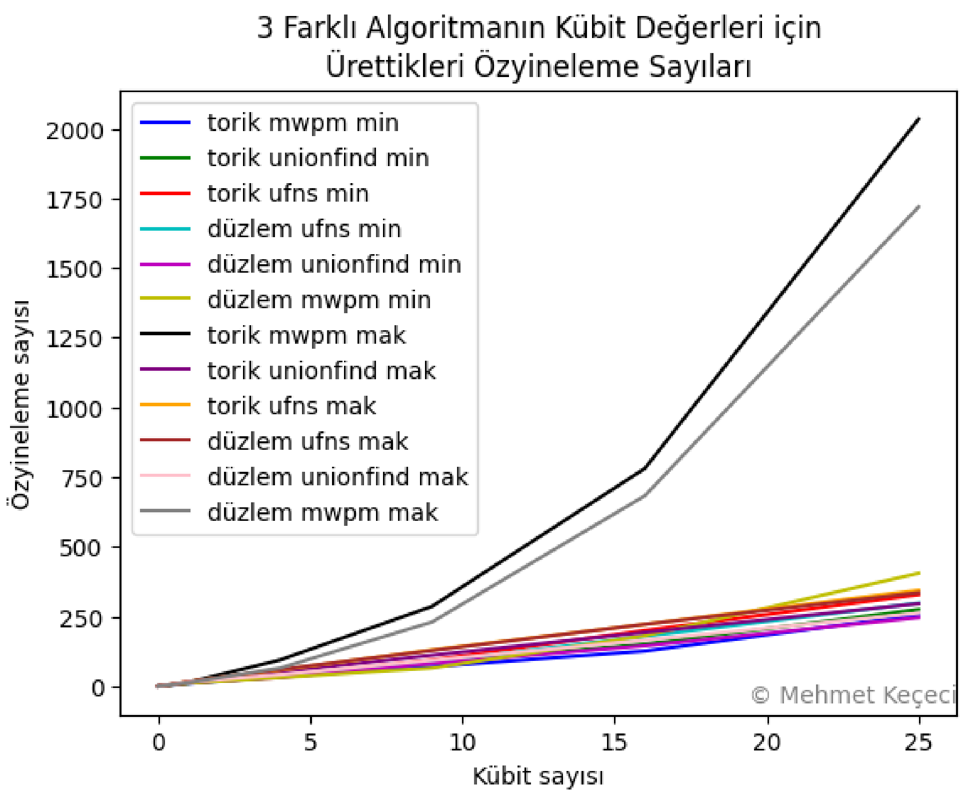


Figure: Minimum and maximum recursion values with and without applied errors.



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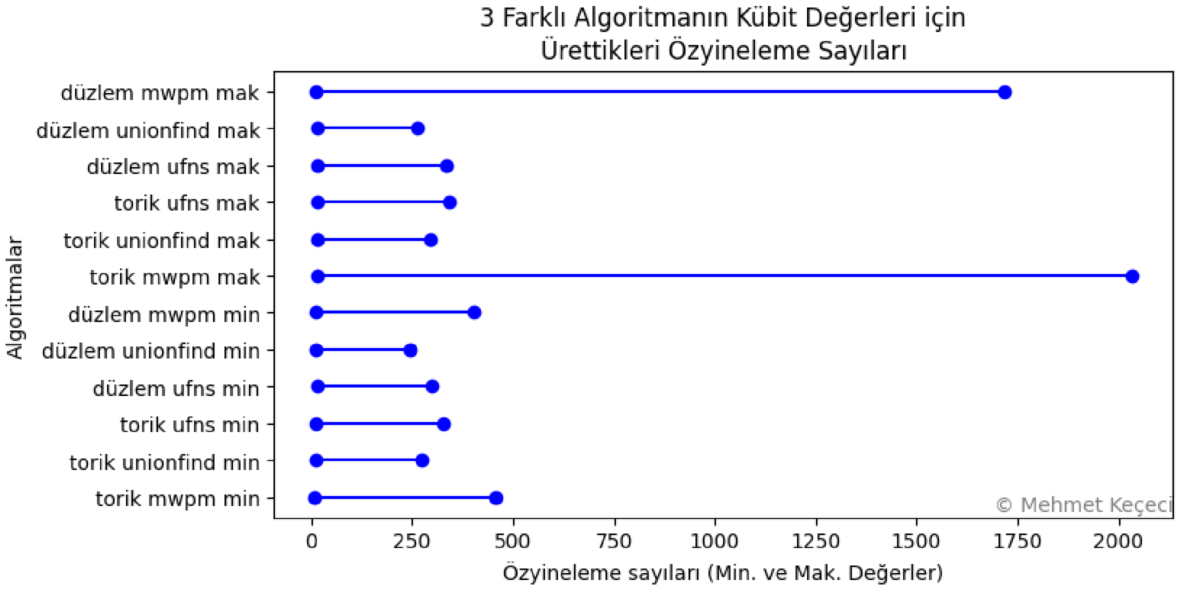


Figure 85: Minimum and maximum recursion values with and without applied errors.

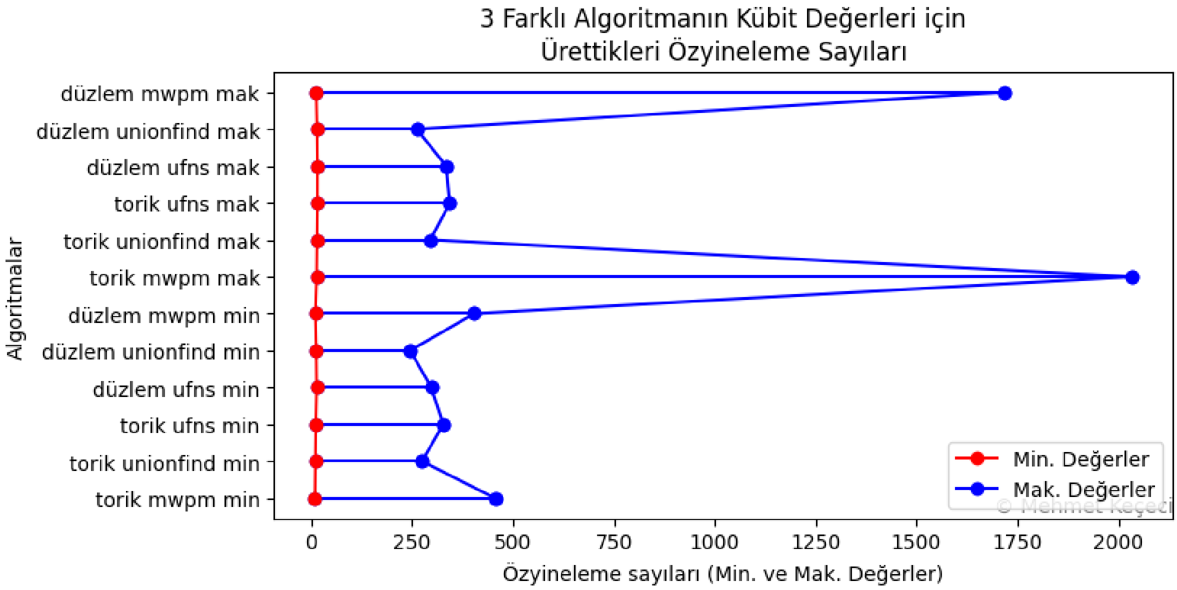


Figure: Minimum and maximum recursion values with and without applied errors.

Circuit Simplification and Optimisation

Simplifying, refining, reducing circuit counts, and optimising growing circuits are of paramount importance for high qubit counts and depth values. Values that should be obtained within 1 hour can sometimes fail to be obtained in 24 hours or hit system limits due to an incorrect algorithm choice. An optimisation study of this kind exists [277, 278].

The visualisations, for which I typically select colour palettes inspired by Turkish, Ottoman, and İznik ceramic tones, generate "mosaic patterns" at low qubit counts and "kilim patterns" (a style of traditional flat-woven textile) at high qubit counts. Furthermore, in our 2D plane and 3D qubit cube visualisations at high qubit counts, the darkening of colours reveals distinct patterns.

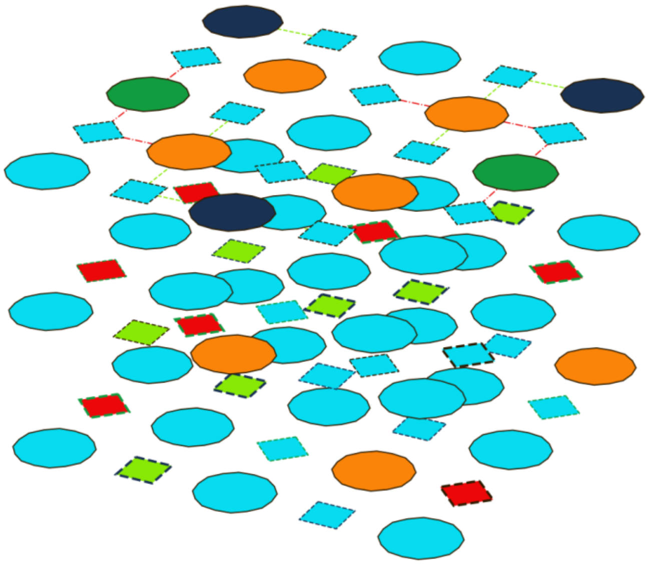


Figure 87: 3x3x3 = 27 Qubits, Dimension: 3, Error Count: 6, p=0.8, Surface Code: Planar, Algorithm: Union-Find.

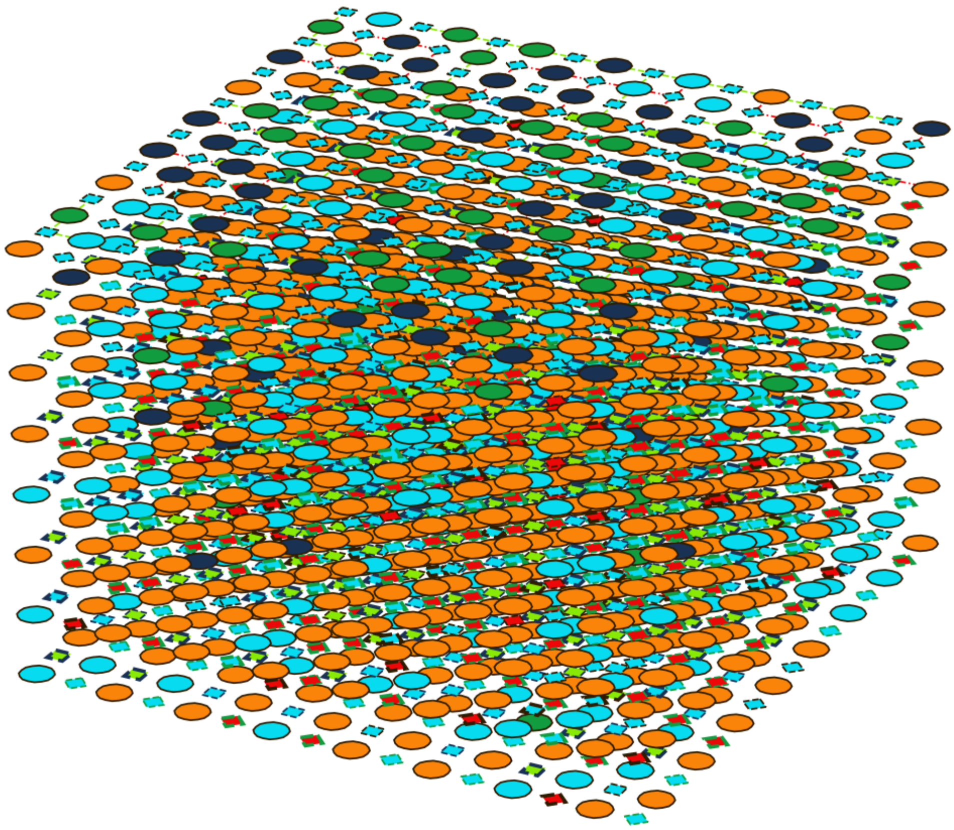


Figure 88: 8x8x8 = 512 Qubits, Dimension: 3, Error Count: 7, p=0.8, Surface Code: Toric, Algorithm: Union-Find.

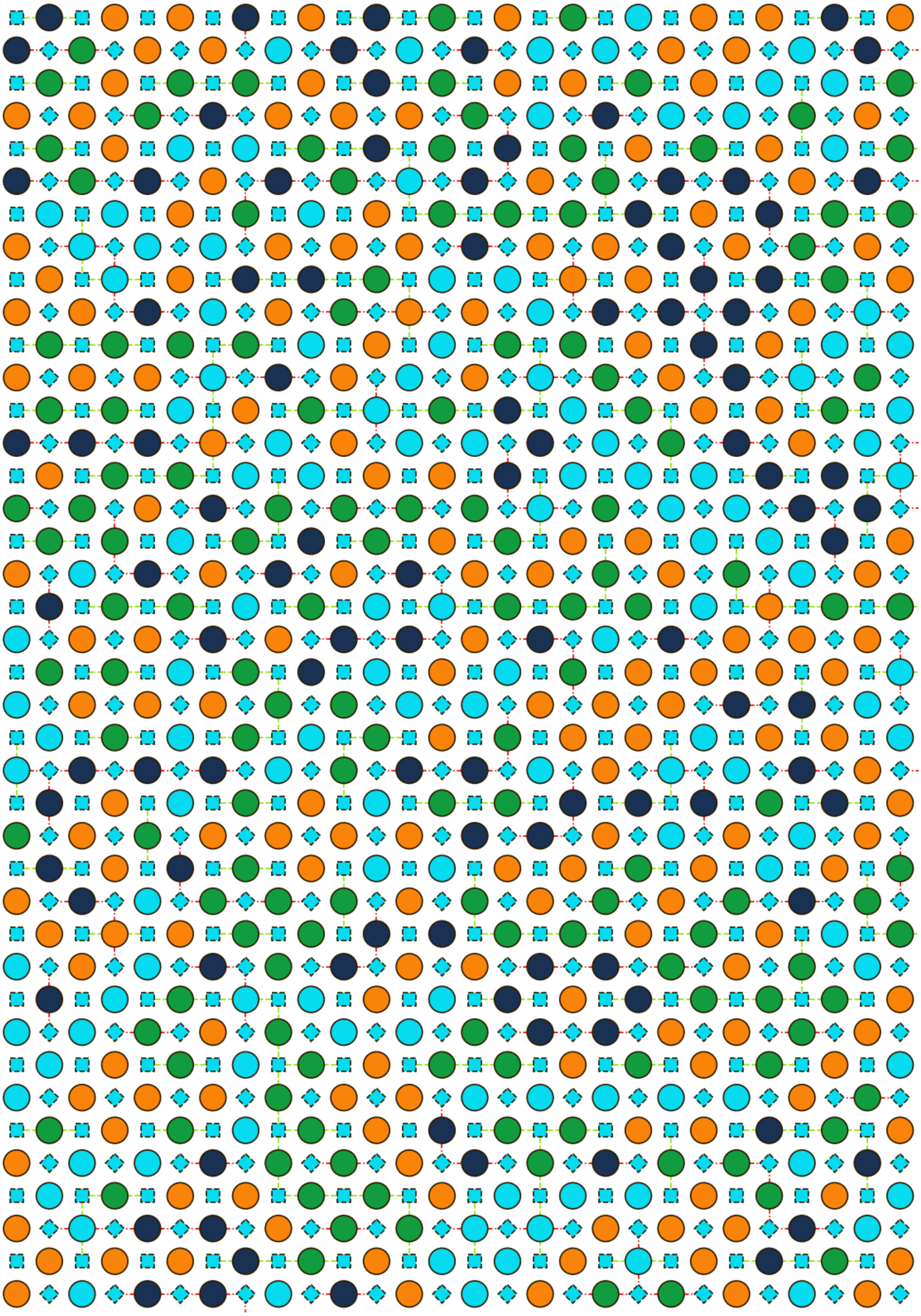


Figure 89: Decoded state of errors. 14x20 = 480 Qubits, Surface Code: Toric, Algorithm: Union-Find, Error Count: 7, p=0.8.

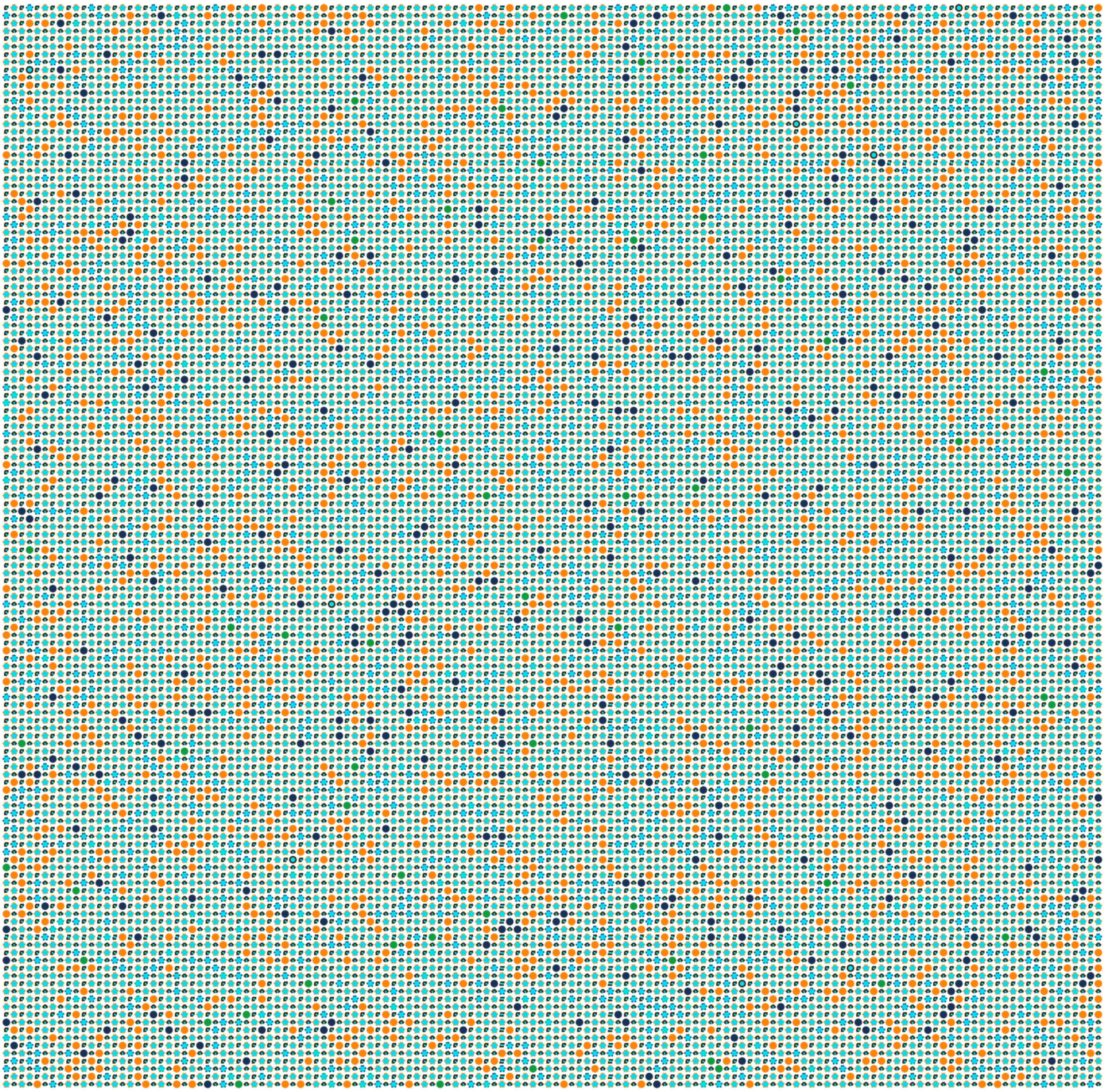
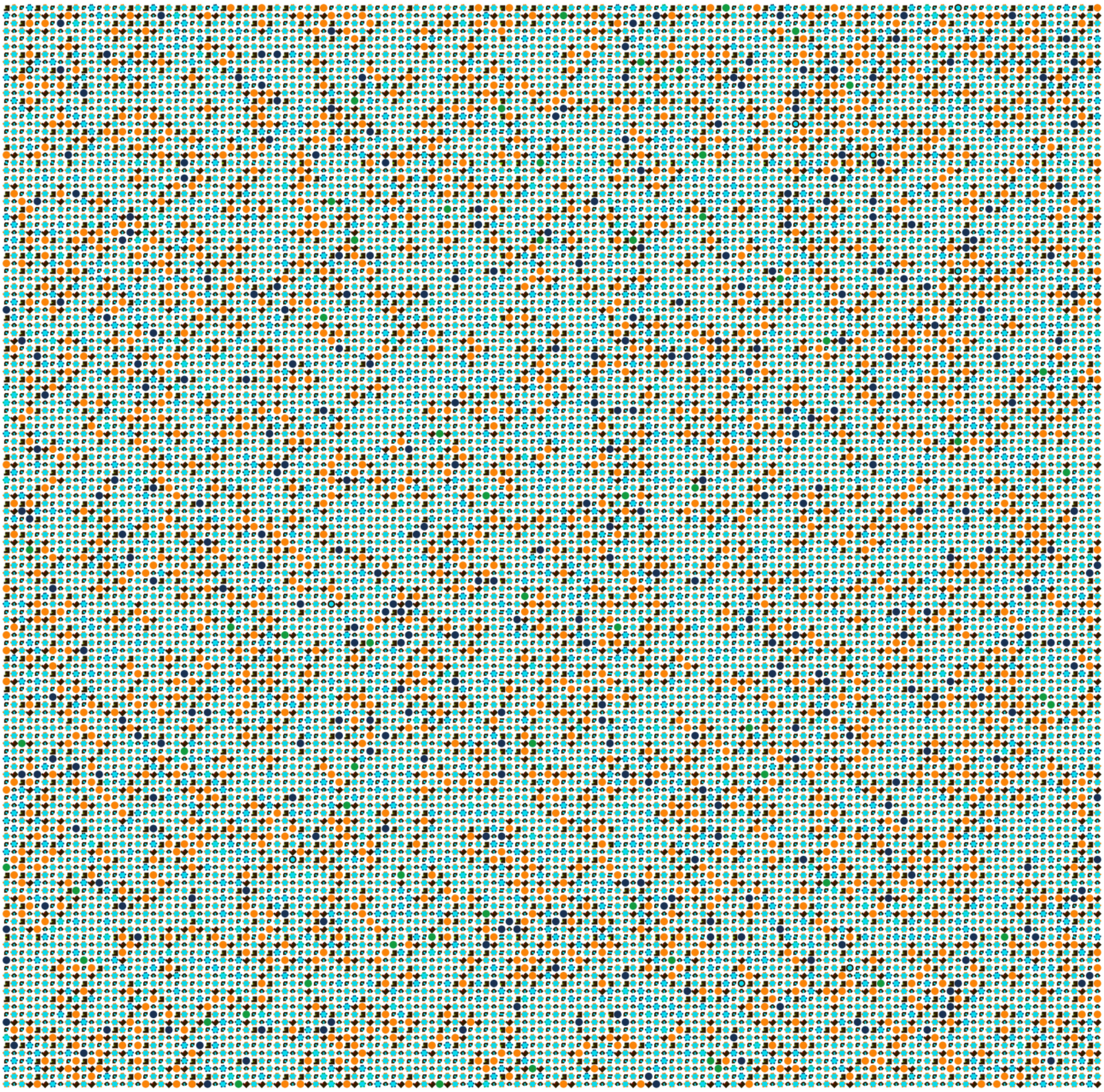


Figure 90: 71x70 = 4970 Qubits, Qubits: (0,0). Surface Code: Toric, Algorithm: UFNS, Dimension: 2, Error Count: 6, p=0.8. State with erroneous codes applied.



Figures 91: Stages of error correction for a sample case (Ancilla measurement, cluster finding, growing, peeling, final decoded state with 6 errors resolved). Recursion count: 21,141,897.

Figure 92: Cluster finding

Figure 93: Cluster growing

Figure 94: Cluster peeling.

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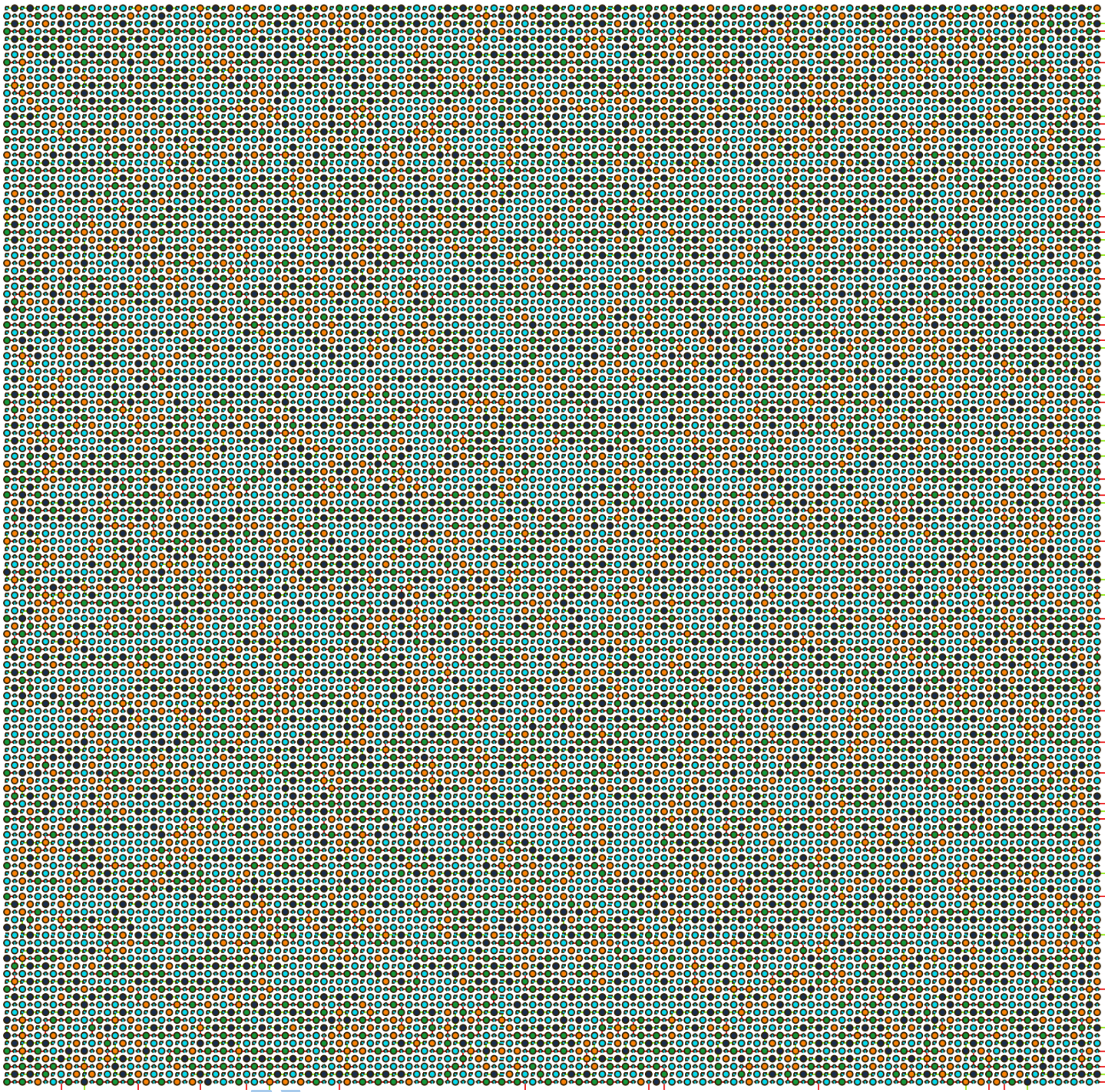

Figures 95: Stages of error correction for a sample case (Ancilla measurement, cluster finding, growing, peeling, final decoded state with 6 errors resolved). Recursion count: 21,141,897.

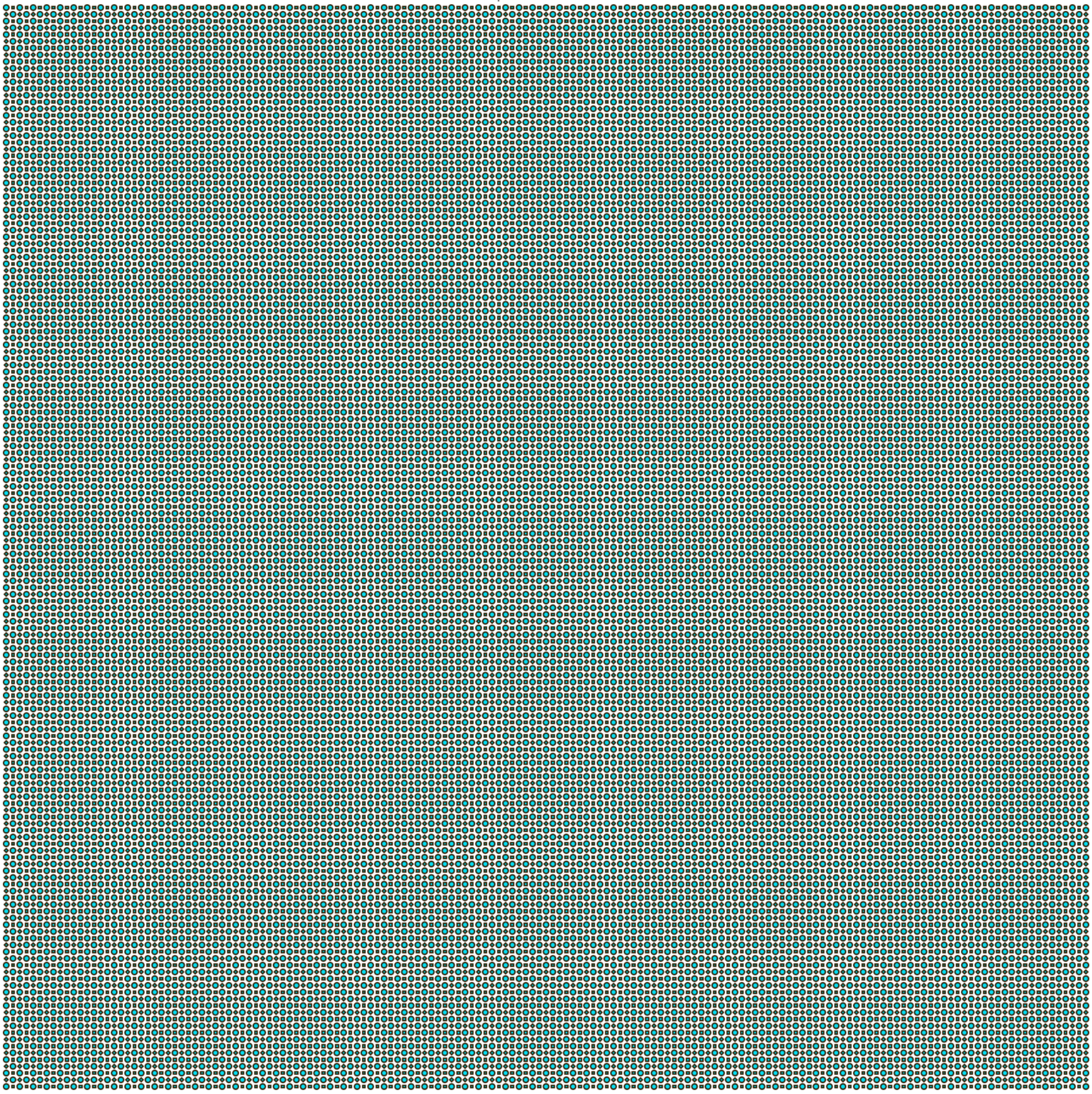

Figure 96: 81x81 = 6561 Qubits. Dimension: 2, Qubits: (0,0). Surface Code: Planar, Algorithm: MWPM, Error Count: 6, p=0.8.

- *Explanation:* Here, we first place error-free qubits and assign all the qubit values as (0,0). We could also assign them as (0,1) or (1,1); the final result would not change. However, since I assign a colour code to each qubit state, the initial colours would be different.
- Planar codes produce fewer recursions as qubit counts increase, leading to faster solutions. This is the reason for choosing the planar surface code. However, planar codes can only be selected as square codes (e.g., 81x81).

- Toric codes, on the other hand, allow for different rectangular dimensions (e.g., 71x70, 71x1). The toric code produced the fewest recursions for a single qubit.

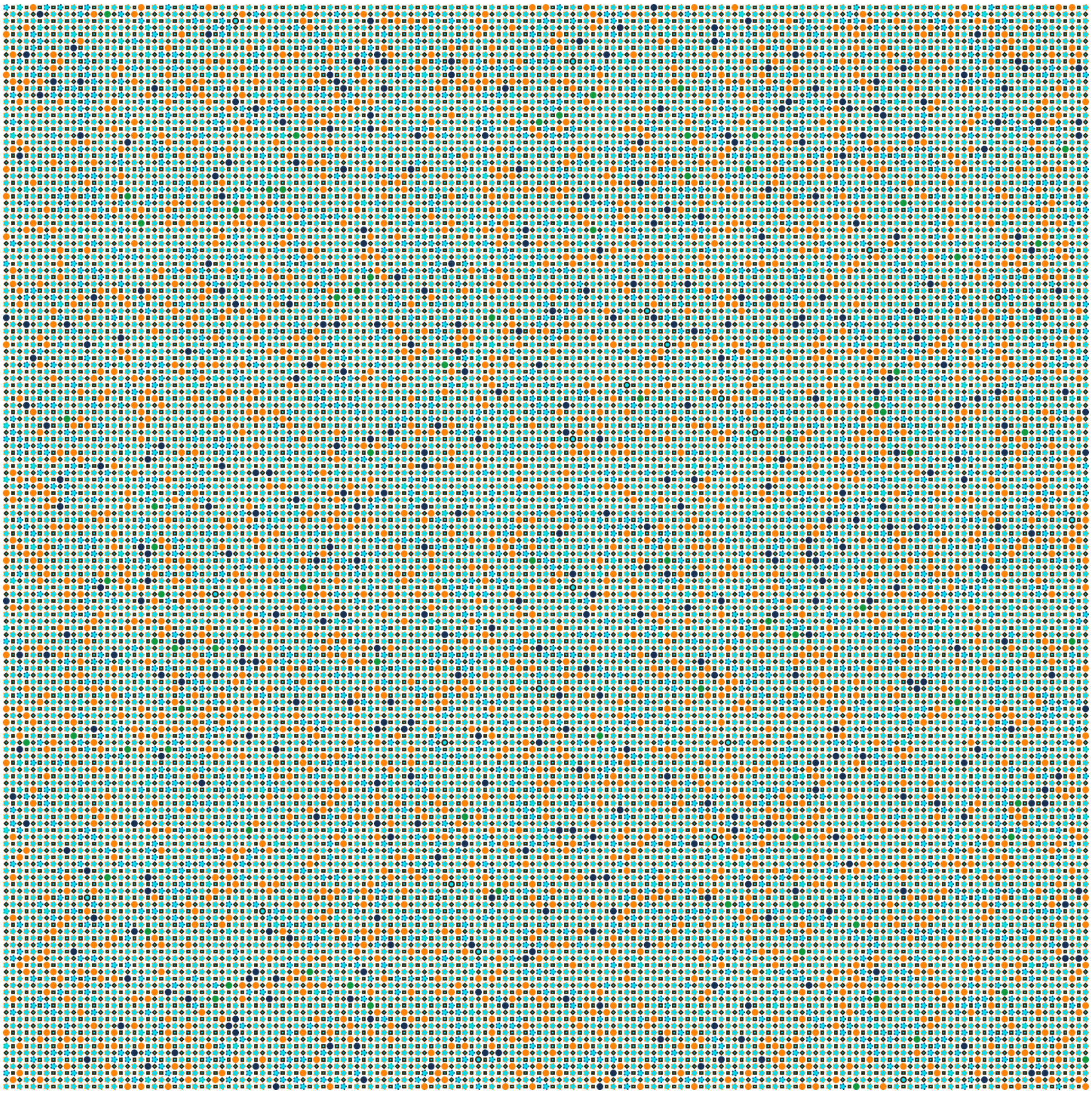

Figure 97: Stages for the 81x81 = 6561 qubit case (Errors applied).

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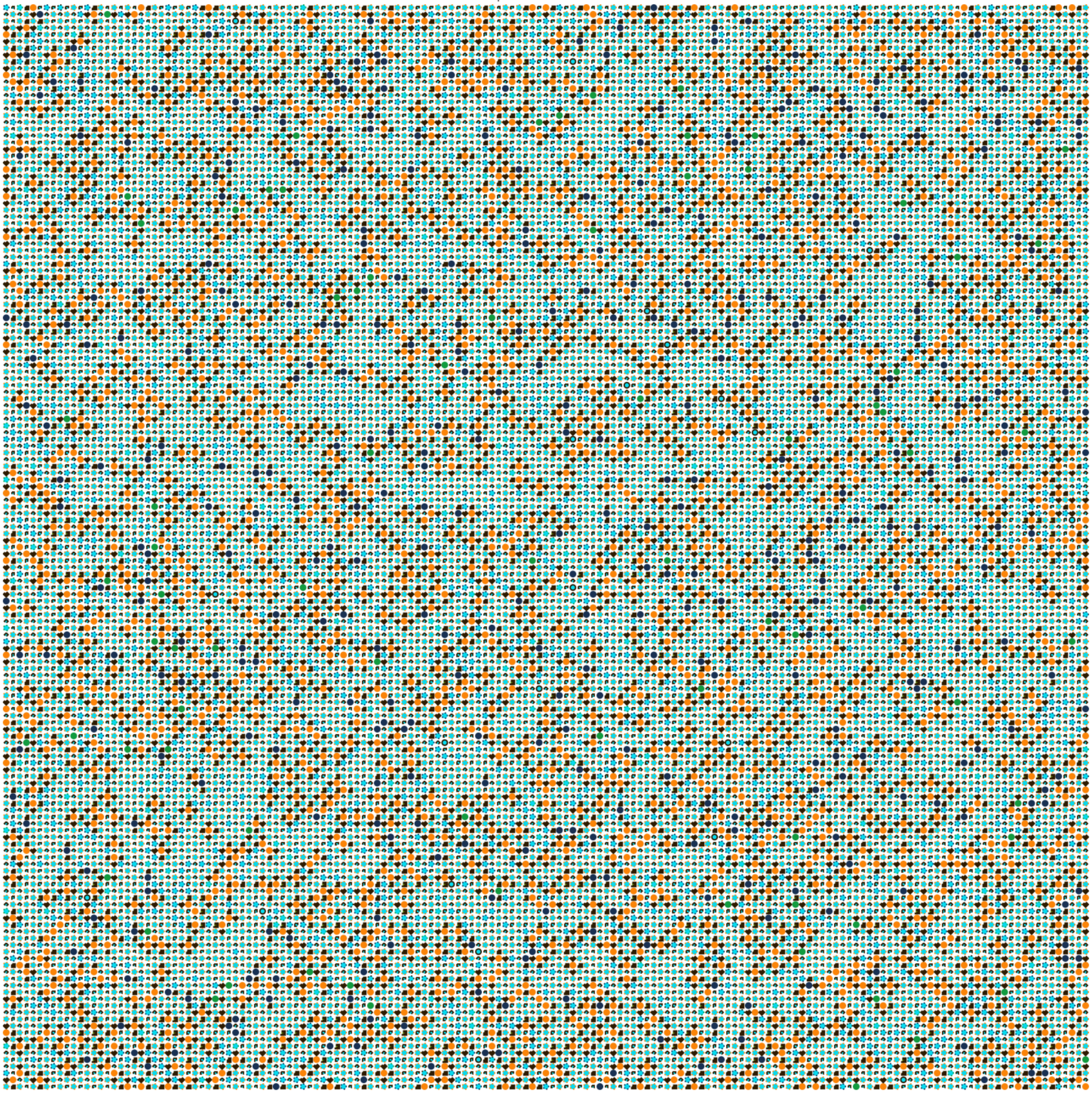

Figure 98: Stages for the 81x81 = 6561 qubit case (ancilla measured).

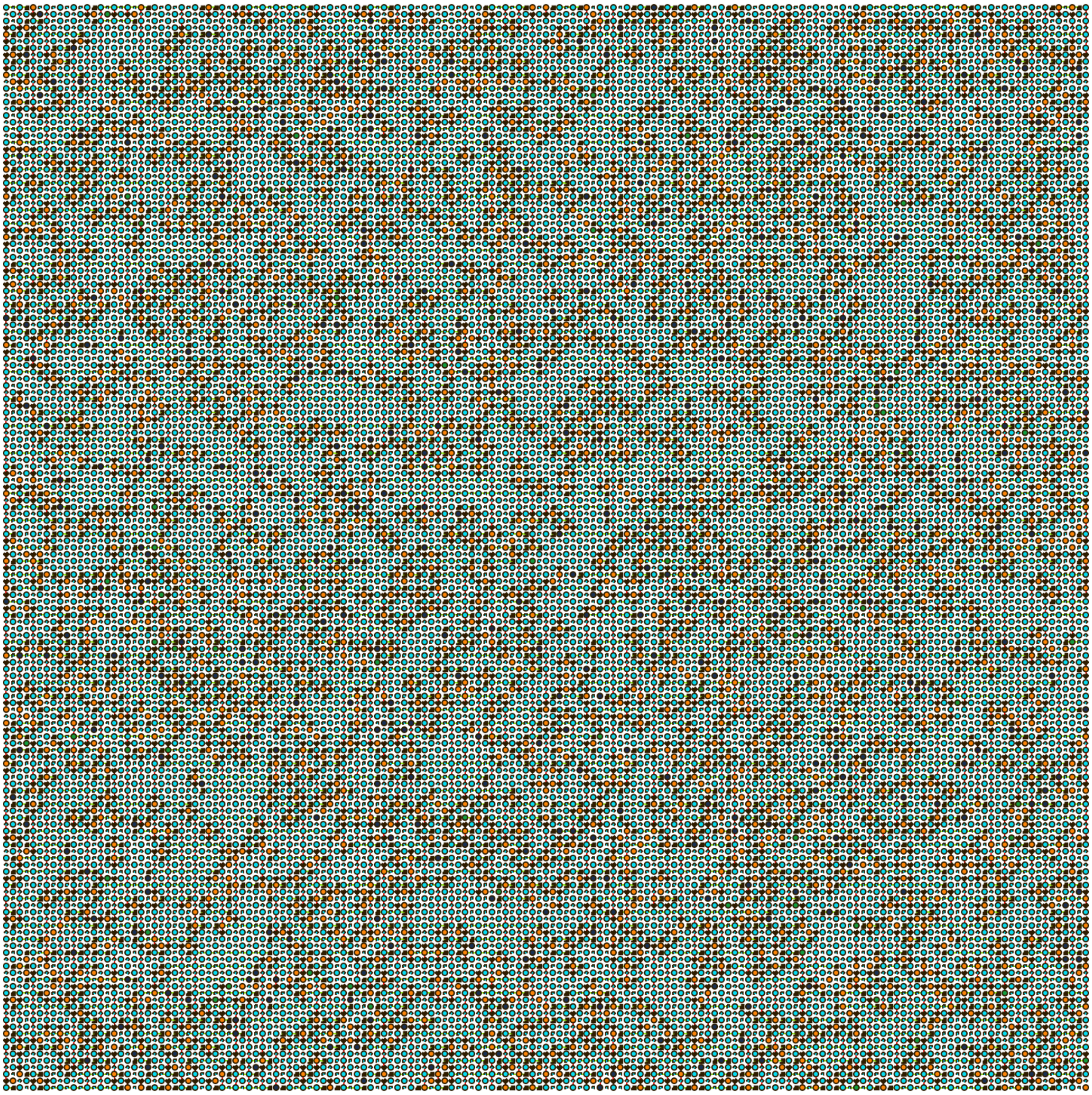

Figure 99: Stages for the 81x81 = 6561 qubit case (clusters matched).

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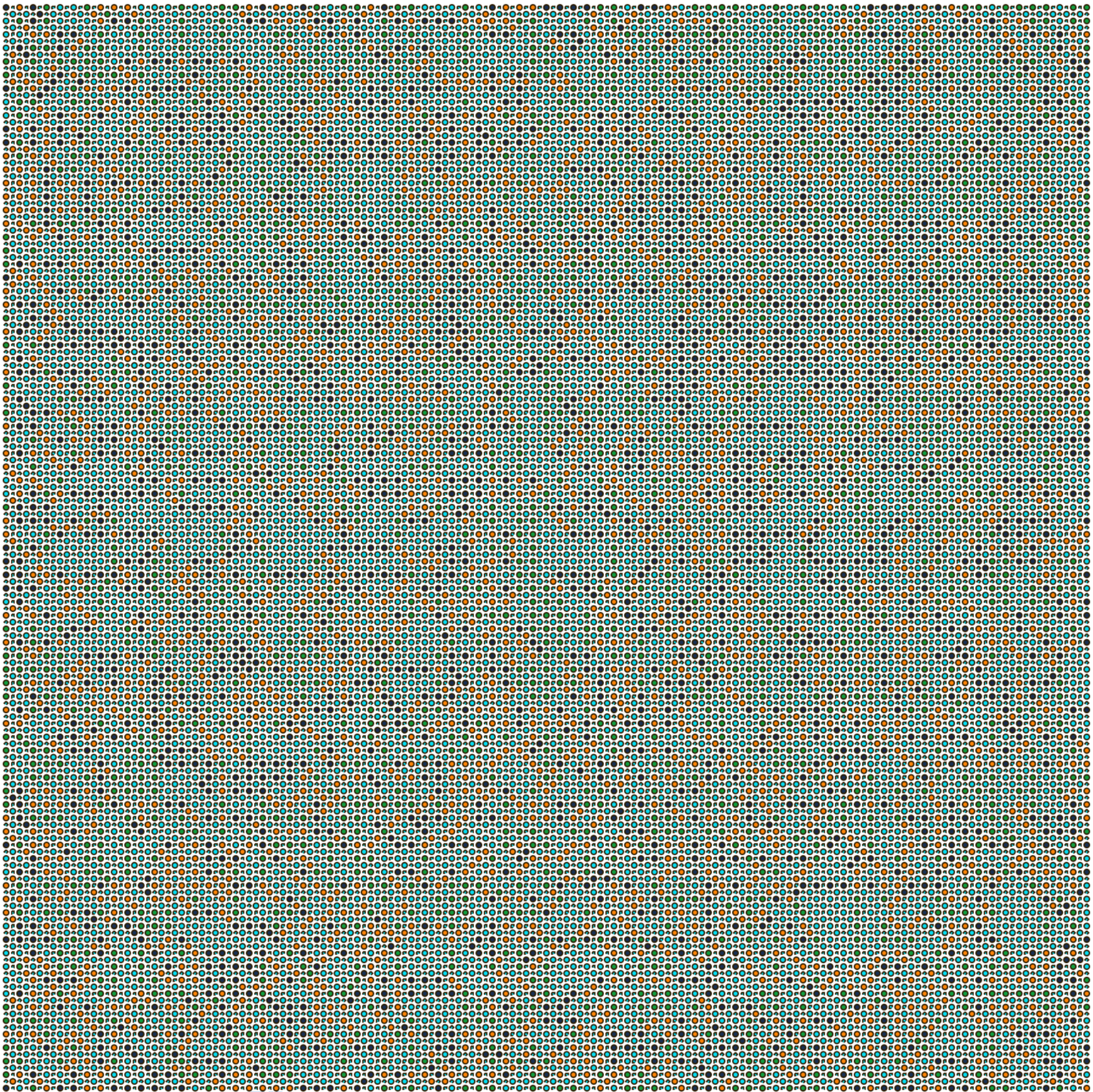


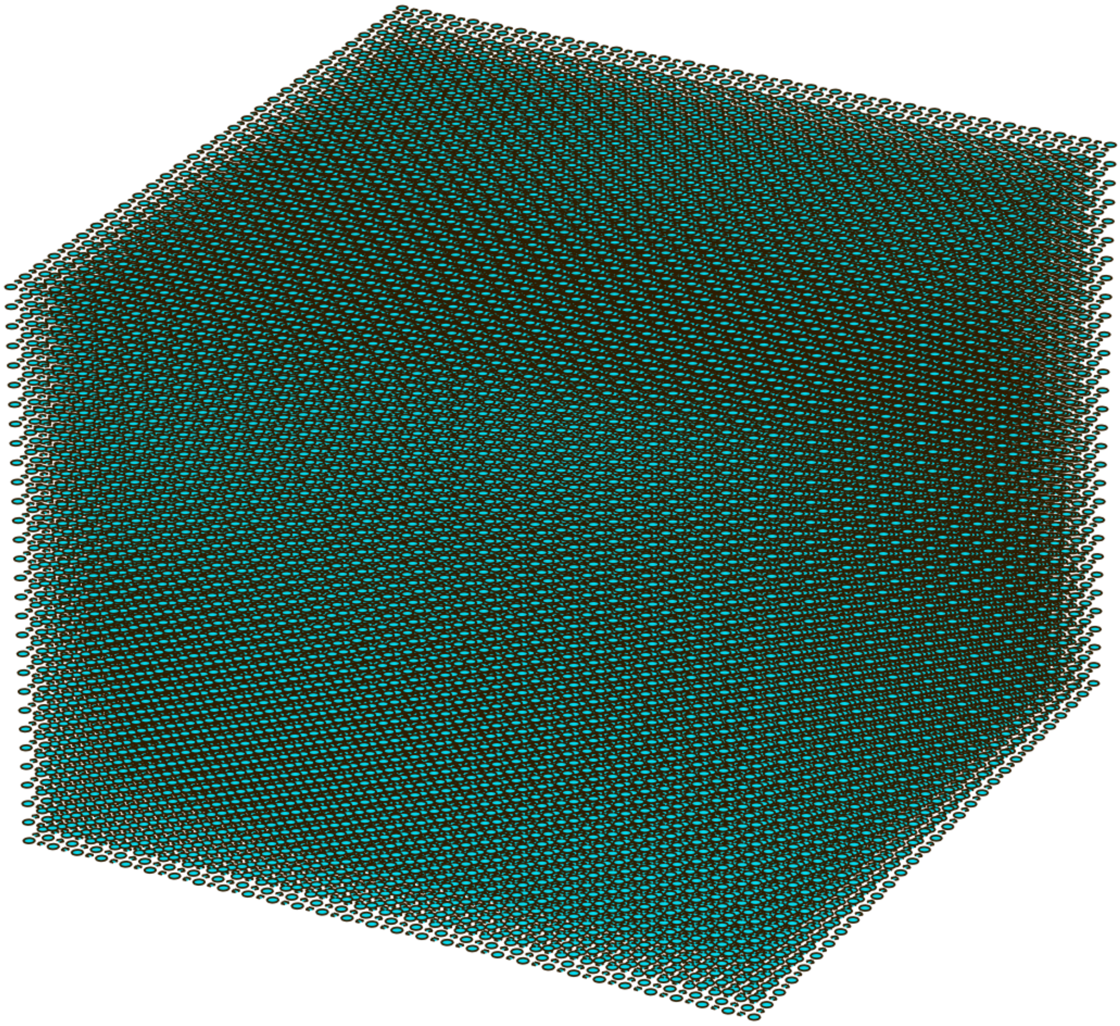
Figure 100: Stages for the 81x81 = 6561 qubit case (errors decoded).

- Mean code execution time: 31.658993048 hours
- Recursion count: 7,692,331,778

```
Kodun ortalama çalışma süresi: 113972.374971600 saniye
Kodun ortalama çalışma süresi: 1899.539582860 dakika
Kodun ortalama çalışma süresi: 31.658993048 saat
Özyineleme (recursion) sayısı:  7692331778
```

Figure 101: Analysis data.

The reason for the long resolution time (~31.66 hours) was the selection of the MWPM algorithm, which generates a very high number of recursions (7,692,331,778). Here, the system's permitted limit was exceeded by a factor of 3. This can lead to system issues (e.g., Sbox_Fatal_Memory_Exceeded, etc.), but the algorithm managed to bypass the system's constraint using its internal dynamics to reach a solution. As this is a licensed algorithm, I did not apply the optimisation methods I used on the others.



Figures 102: Stages for a 30x30x30 = 27,000 Qubit Cube. Dimension: 3, Qubits: (0,0). Surface Code: Planar, Algorithm: Union-Find, Error Count: 6, p=0.8. (Initial state).

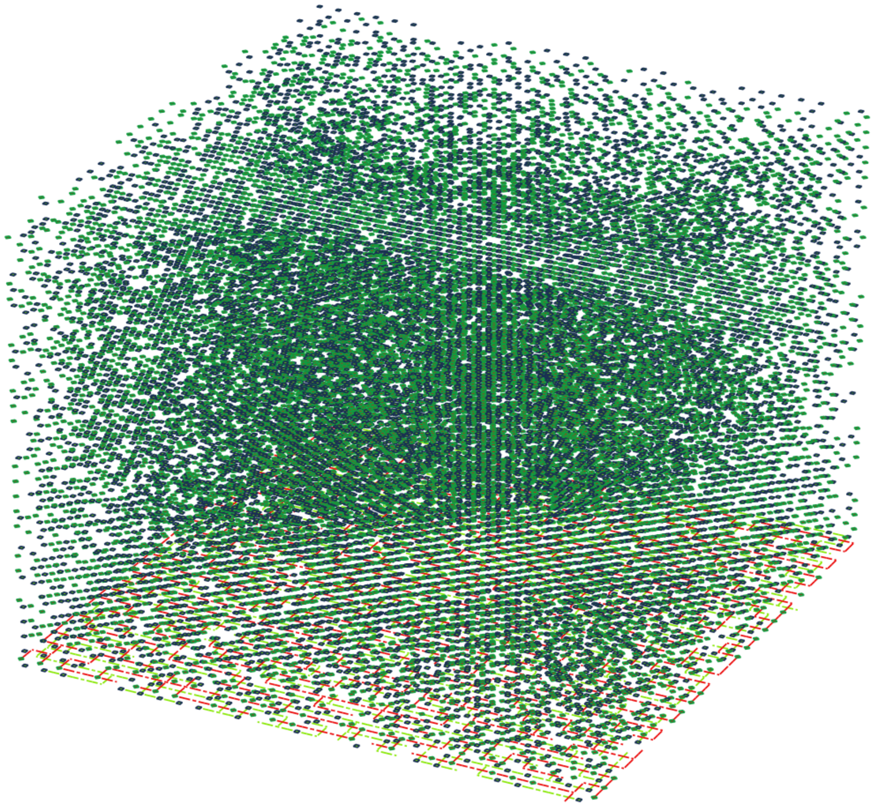


Figure 103: clusters found

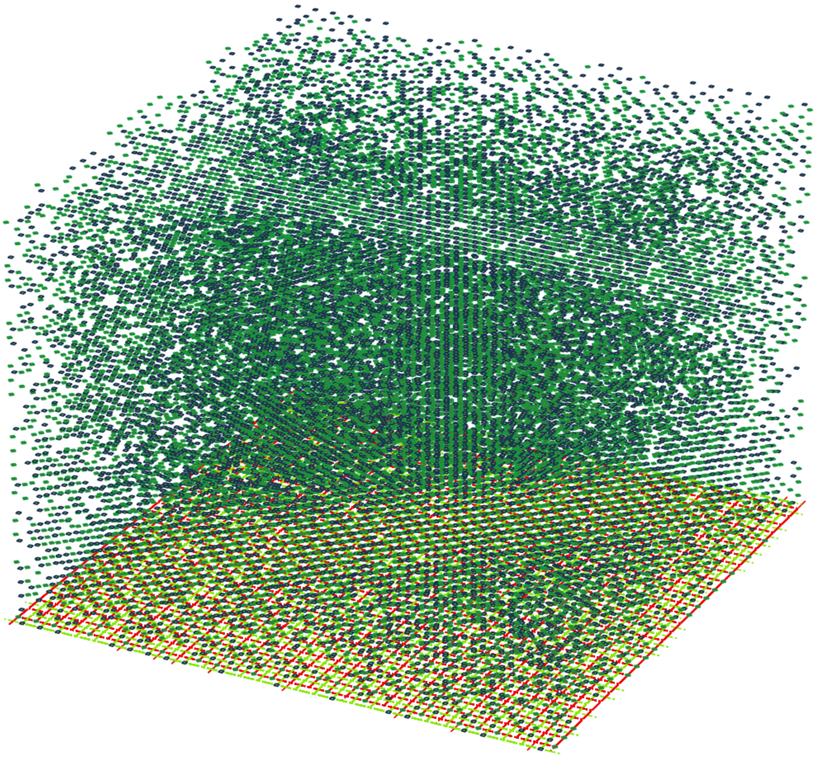


Figure 104: clusters grown

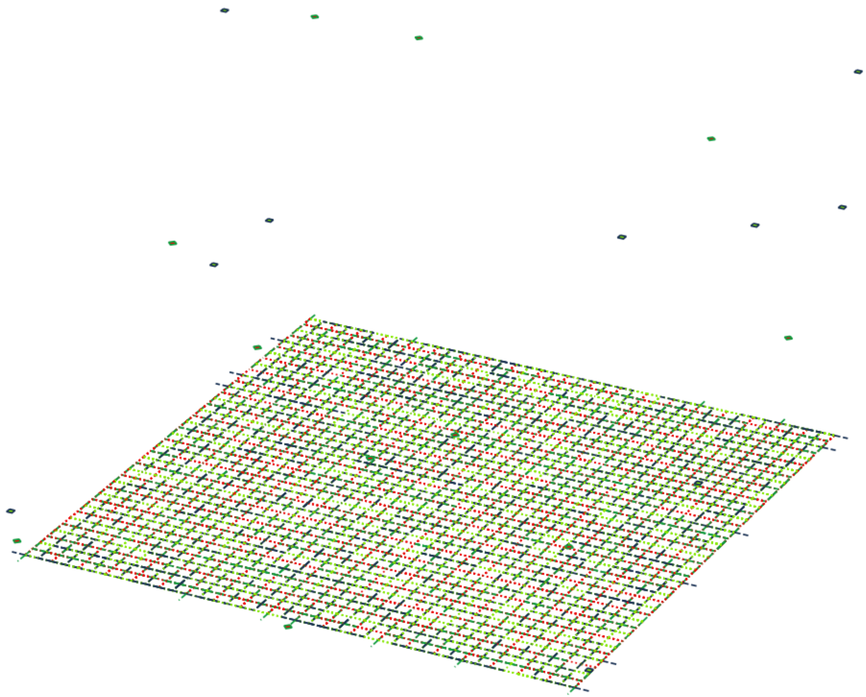


Figure 105: clusters peeled

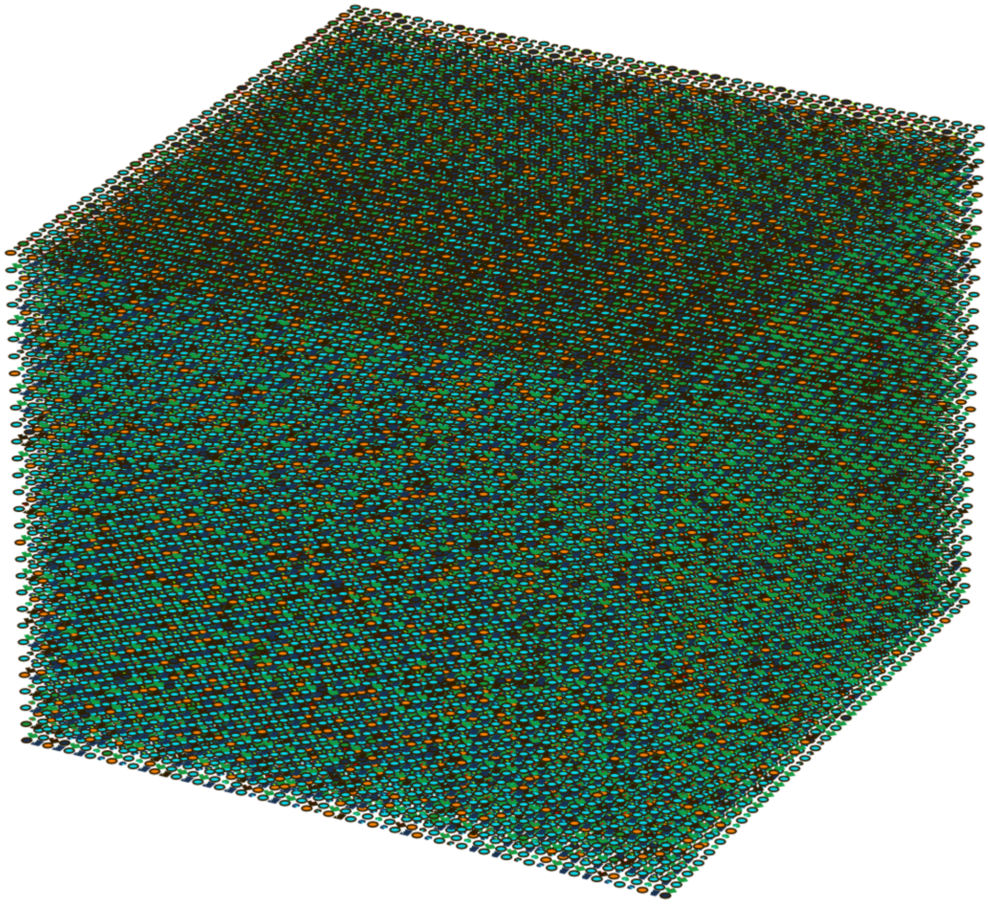


Figure 106: final decoded state

- Mean code execution time: 15.182610668 hours
    - Recursion count: 964,118,273

```
Kodun ortalama çalışma süresi: 54657.398405900 saniye
Kodun ortalama çalışma süresi: 910.956640098 dakika
Kodun ortalama çalışma süresi: 15.182610668 saat
Özyineleme (recursion) sayısı:  964118273
```

Figure 107: Analysis results.

Qubit Count	1D Recursion Count: 2023 Results (Error-Free / Min with Errors / Max with Errors / With Errors) System Maximum Allowed Value: 2,147,483,639		2D	3D
Non-Graphic	Toric	Planar	Planar-Toric	Planar-Toric

al Solution				
1	**MWPM: 8-15** Union-Find: 9-16 UFNS: 10-17	**MWPM: 9-14** Union-Find: 11-16 UFNS: 12-17	25215-27898-46157	27503-34064-45071
4	MWPM: 19-34-94 Union-Find: 20-35-51 UFNS: 21-34-58	MWPM: 20-**31**-65 **Union-Find: 22-31-41** UFNS: 23-33-60	36878	
9	MWPM: 39-70-286 Union-Find: 40-85-111 UFNS: 41-94-130	MWPM: 40-65-230 Union-Find: 42-82-93 UFNS: 43-86-128	64317	
10	MWPM: 231 Union-Find: 94-116 UFNS: 102-133			37613065
16	MWPM: 67-126-683 Union-Find: 68-151-193 UFNS: 69-200-222	MWPM: 68-181-683 Union-Find: 70-145-165 UFNS: 71-179-222	90389-90726	
25	MWPM: 103-256-2034 Union-Find: 104-275-296 UFNS: 105-328-344	MWPM: 104-405-1719 Union-Find: 106-246-262 UFNS: 107-298-335	106436-707964	
81	Union-Find: 810-887	853-855	339974-5359385	1169514
100	MWPM: 403-3994-37881 Union-Find: 404-442-502	Union-Find: 1049-1072	448495-2871616	
225		2383	1171338-9723032	
400		4327	2375979	
900		9815	18262090	

1000	MWPM: 2602179 Union-Find: 11088-11403			12604112-37613065
1024		Union-Find: 11279		
1225		13492	38965022	
1600		17612	94371068	
2500	Union-Find: 33933	27620	12680084-310027077	
3375				977942346
3600		39859		
4900		54365	20831934	
4970			21141897	
5184		57519	Union-Find: 21.716.983	
6561		72901	**MWPM: 7.692.331.778**	
10000	Union-Find: 111753-112739	Union-Find: 111358	2024-2025	
12167			2024-2025	335795270
20000	Union-Find: 225855		2024-2025	
27000			2024-2025	Union-Find: **964.118.273**
40000	Union-Find: 450881-450977	Union-Find: 446017	2024-2025	
125000			2024-2025	**2024-2025**
160000			**2024-2025**	
2496400		Union-Find: 27.933.973		
3240000		Union-Find: 36.253.303		

4000000		Union-Find: **44.841.873**		
5000000	**2024-2025** Results			

Table 16: Recursion counts generated by algorithms during error correction.

Note: No error was applied for the 1-qubit minimum recursion case. The recursion count increases with the number of errors. The 7th error type (rotation error) was added more recently (the error count reached 17 in 2025), hence it is absent from earlier measurements. Each additional error type contributes to an increase in recursion.

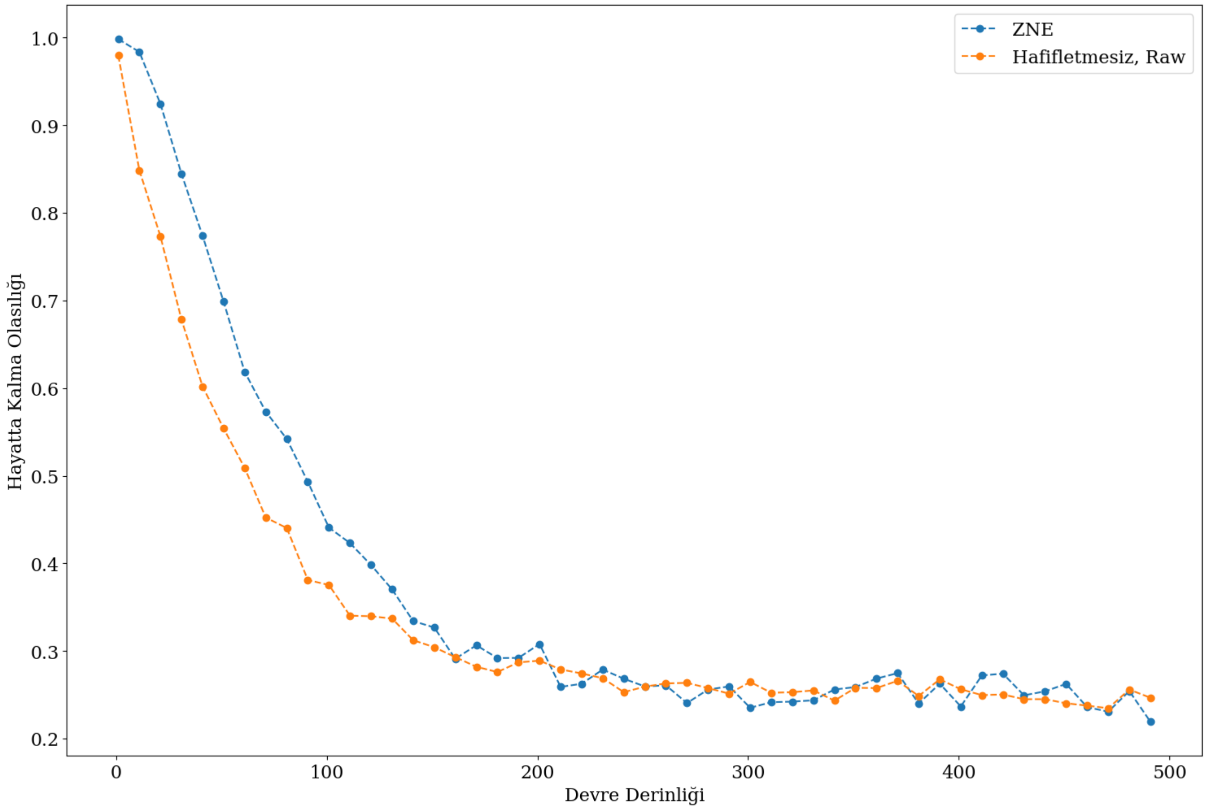


Figure 108: Circuit depth obtained using the ZNE (Zero-Noise Extrapolation) algorithm over ~5 hours, respectively.

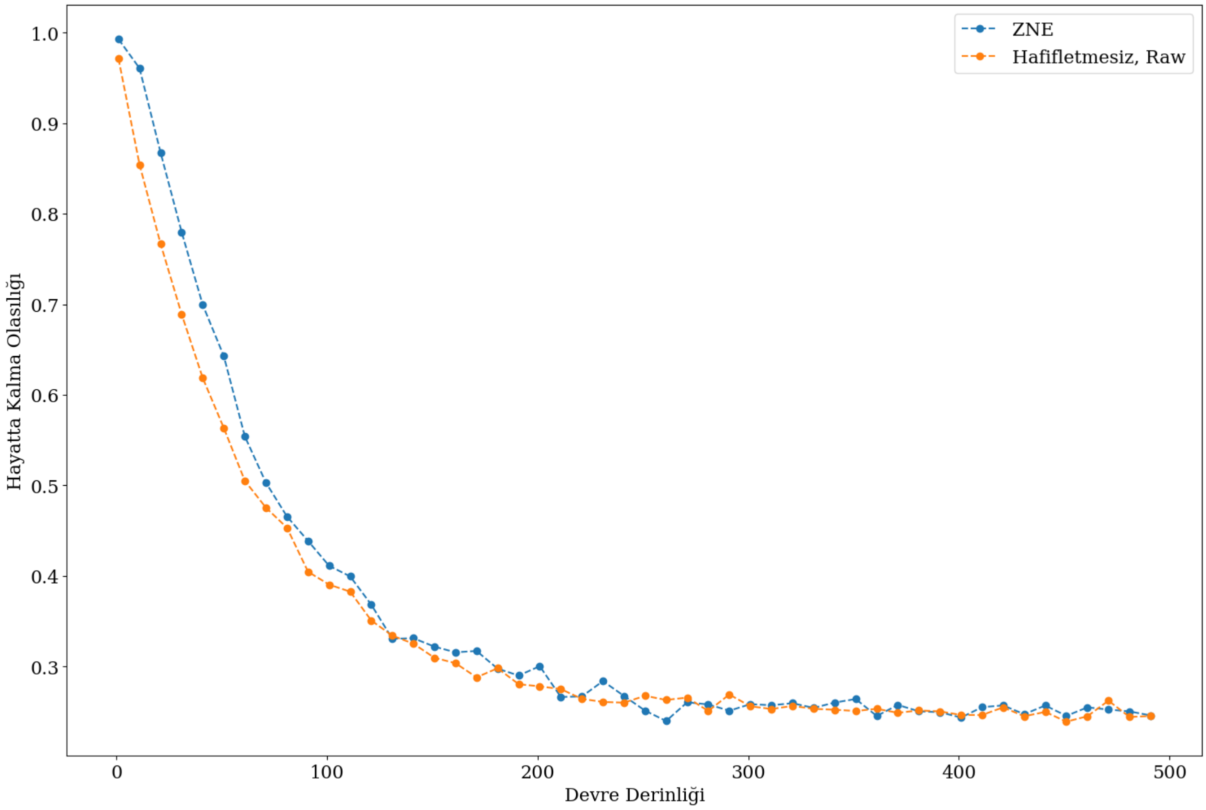


Figure 109: Circuit depth obtained using the ZNE (Zero-Noise Extrapolation) algorithm over ~18 hours, respectively.

- **Note:** The fact that the mitigated ZNE starts above the ideal value of 1 is due to the mitigation approach sometimes yielding values either below or above 1.
- The mitigated ZNE algorithm yields good results at low circuit depths. Although mitigation is applied to the ZNE algorithm, beyond depths of 130-220, mitigation alone becomes insufficient. Therefore, using algorithms in tandem—first calibration, followed by a second or multiple algorithms—proves more effective. While this value may suffice for simulating an average level of fidelity, it will be inadequate for advanced applications or cryptographic solutions.

Topological Gap Protocol (TGP) [279, 280] is a method used to verify the topological protection of topological superconductors. The controllability and preservation of Majorana zero modes are critical for topological quantum computation. TGP is a protocol developed to test the usability and topological protection of topological superconductors. It confirms the energy gap (topological gap) necessary for a topological superconductor to provide topological protection. If this energy gap is sufficiently large, it signifies that topological protection is achieved and the Majorana zero modes are stable.

III. The Future of Quantum Error Correction: Towards Recursive Excellence, Mastery of Extreme Noise, and the Quantum Leap

The Future Perspective and Concluding Remarks on Quantum Error Correction

On the journey towards realising quantum computers, Quantum Error Correction (QEC) indisputably remains one of the most critical and challenging research areas. Although the theoretical and experimental progress achieved to date is promising, significant obstacles must be overcome to construct a universal, fault-tolerant quantum computer. Foremost among these are the efficiency and scalability of QEC algorithms, and their resilience against increasingly complex noise models. Within the context of "Recursion Optimisation and Extreme Noise Tolerance in Quantum Error Correction Algorithms," it is possible to assess the key future research directions and potential milestones in this field.

1. Algorithmic Excellence and Hardware-Software Co-Design:

The future will inevitably involve the further refinement and optimisation of existing QEC decoder algorithms, such as MWPM, Union-Find, and their variants. Recursion optimisation will retain its vital importance for the simulation of large-scale systems and for potential real-time decoding. However, software optimisation alone may not suffice. The co-design of hardware architectures and QEC algorithms will gain increasing prominence. For instance, it may be necessary to develop decoders optimised for specific qubit technologies (superconducting, ion trap, photonic, Majorana-based, etc.) and their unique noise characteristics. Specialised hardware, such as FPGAs (Field-Programmable Gate Arrays) or ASICs (Application-Specific Integrated Circuits), could play a critical role in accelerating QEC operations.

The integration of Artificial Intelligence (AI) and Machine Learning (ML) techniques into the QEC field is also a promising direction. ML models could be used to recognise complex error syndromes, learn more efficient decoding strategies, or even discover new QEC codes. In particular, reinforcement learning approaches offer potential for developing decoders capable of adapting to dynamic and unknown noise environments.

2. Novel Code Families and Error Tolerance Paradigms:

Although surface codes are currently one of the most studied and promising code families, the discovery of new code families with higher code rates (encoding more logical qubits with fewer physical qubits) and/or better error thresholds will continue. Quantum LDPC (Low-Density Parity-Check) codes, the quantum analogues of classical LDPC codes, hold significant potential in this regard, although the design of efficient decoders for them remains an active research topic.

Topological quantum computation, centred around Majorana fermions and non-Abelian anyons in general, will continue to attract intense interest due to its potential for inherent error tolerance. The experimental demonstration of the definitive creation, manipulation, and braiding of Majorana Zero Modes (MZMs) remains a primary challenge in this area. If successful, such systems could significantly reduce the overhead required for QEC and represent a major milestone on the path to a "Quantum Leap."

3. Managing Extreme and Realistic Noise Models:

The noise in quantum systems is far more complex than simple, independent errors. Correlated errors (where an error on one qubit triggers errors on neighbouring qubits), coherent errors (systematic errors like phase accumulation), and time-varying, qubit-specific error rates can profoundly impact QEC performance. Future QEC strategies must be more resilient against such "extreme" and realistic noise models. This will influence both code design and decoder algorithms. For example, decoders may need to account for the spatial and temporal correlations of noise.

The concept of "Extreme Noise" is expected to be further refined, leading to the development of specialised QEC protocols for different extreme noise scenarios. This will necessitate a feedback loop where data from quantum hardware characterisation directly informs the design of QEC strategies.

The Quantum Leap and Beyond:

The "Quantum Leap"—the emergence of a quantum computer capable of solving problems intractable for classical computers—is one of the ultimate goals of QEC. While it remains uncertain when and on which platform this leap will occur, inherently low-noise or noiseless approaches, such as those based on MZMs, could play a pivotal role. However, even these platforms will not be perfect and will require optimised and efficient QEC mechanisms.

Beyond the Quantum Leap, the widespread availability of universal, large-scale, fault-tolerant quantum computers has the potential to revolutionise countless fields, from materials science and drug discovery to artificial intelligence and cryptography. Realising this long-term vision will depend on continuous innovation and interdisciplinary collaborations within the QEC field.

Concluding Remarks:

Quantum error correction is the most critical bridge between the concept of quantum computing and its realisation. Seemingly technical details, such as recursion optimisation, are fundamental elements that directly impact the feasibility of large-scale systems. Developing QEC schemes that can function even under extreme noise conditions is indispensable for the reliable use of quantum computers in practical applications.

Innovative approaches like Majorana fermions and topological quantum computation offer a different perspective on the noise problem, promising a potential paradigm shift. However, these approaches will also face their own challenges and QEC requirements.

The future will be an era where QEC algorithms become more intelligent, operate in closer integration with hardware, new and more powerful codes are discovered, and, most importantly, the complex nature of noise in quantum systems is better understood, leading to tailored solutions. Every step taken on this challenging yet exciting journey will bring us closer to the transformative future promised by quantum technologies. Whether we are on the verge of a Quantum Leap, time will tell. Nevertheless, the research directed towards this goal and the successes achieved continue to push the boundaries of science and technology. Progress in QEC will contribute not only to the development of quantum computers but also to a deeper understanding of fundamental physics, as exemplified in my previous publications [119, 120, 291–343].

In conclusion, the future of quantum computing is being forged on the delicate boundary between chaos and order. This work has aimed to be a small yet significant step in favour of order within this arduous quest, spanning from the depths of recursion to the vortex of extreme noise.

Not: The references provided here correspond to the first part of a prior study and are therefore not numbered or ordered based on their appearance in this paper. Additional citations introduced after the original submission are also omitted from the main reference list for consistency [322–473].

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