події. Жодного перемикання між консолями, аналітик бачить висновок системи машинного навчання там, де і всі інші події, а система аналізує збагачені дані.

Попередні лабораторні тести на відкритому датасеті CIC-IDS2017 підтвердили принципову працездатність підходу та прийнятні метрики класифікації для більшості представлених класів атак. Повна валідація методології в умовах реального виробничого середовища запланована на наступному етапі дослідження. Відповідно, кількісні оцінки впливу на середній час виявлення наразі не наводяться.

В роботі представлено методологію збагачення подій структурованими метаданими машинного навчання в кореляційну логіку SIEM-систем, що базується на класифікації мережевого трафіку моделлю Random Forest з поверненням мітки класу та оцінки впевненості. Ознаковий вектор формується з мережевих метаданих сесій, а результати класифікації передаються в тіло події через поля ml_class, ml_score та ml_features_summary. Це усуває необхідність ручного зіставлення даних між консолями та створює передумови для скорочення часу виявлення загроз.

1. Sharafaldin I., Habibi Lashkari A., Ghorbani A.A. Toward Generating a New Intrusion Detection Dataset and Intrusion Traffic Characterization. Proceedings of the 4th International Conference on Information Systems Security and Privacy (ICISSP). 2018. P. 108–116. URL: https://www.scitepress.org/Papers/2018/66398/
2. Breiman L. Random Forests. Machine Learning. 2001. Vol. 45. P. 5–32. URL: https://link.springer.com/article/10.1023/A:1010933404324
3. Palo Alto Networks. XSIAM Platform Architecture. Technical Whitepaper, Palo Alto Networks. 2024. URL: https://www.paloaltonetworks.com/resources/techbriefs/cortex-xsiam

The Eastin-Knill Theorem: Fundamental Limitations of Quantum Fault Tolerance

UDK 621.395.7 (043.2)

Yevgen Kotukh[1]

Yevhenii Bereznyak Military Academy, [1]yevgenkotukh@gmail.com

The construction of a large-scale universal quantum computer remains constrained by the inherent fragility of quantum states, which are continuously subject to decoherence, dephasing and energy dissipation. Reliable quantum information processing therefore relies on quantum error correction (QEC) codes, in which a single logical qubit is encoded into an entangled state of many physical qubits. Within the framework of fault-tolerant quantum computing (FTQC), logical operations on encoded data must be implemented in a manner that prevents the uncontrolled propagation of physical errors. The principal mechanism that ensures this property is transversality: a transversal logical gate acts as a tensor product of local unitaries on the constituent subsystems, guaranteeing that a single physical fault propagates to at most one qubit per code block [1].

In 2009 B. Eastin and E. Knill established a no-go theorem stating that no nontrivial finite-dimensional quantum error correcting code can support a continuous group of transversal logical gates [1]. An immediate corollary is that no finite-dimensional QEC code admits a universal set of logical gates implemented exclusively by transversal operations. This result imposes a fundamental constraint on every known approach to scalable FTQC and motivates a broad research program aimed at characterizing, quantifying and circumventing this limitation [2,3]. A QEC code is defined as an isometric embedding of a logical Hilbert space into the Hilbert space of a composite physical system. A transversal logical operator is, by definition, a tensor product of local unitaries acting on individual subsystems or fixed-size groups of subsystems. The original argument of Eastin and Knill proceeds by considering the intersection of an arbitrary Lie group of logical unitaries with the group of locality-preserving operators on the code. This intersection is a closed subset of a Lie group and, by Cartan's closed-subgroup theorem, is itself a Lie subgroup [1].

The infinitesimal generators of any continuous transversal symmetry must therefore be expressible as sums of local Hermitian operators. The Knill-Laflamme conditions, however, require that every correctable local operator act on the code subspace as a scalar multiple of the identity, since otherwise local degrees of freedom would carry information about the logical state. Consequently, the Lie algebra of transversal logical operators reduces to global phases, the corresponding Lie group has dimension zero, and the set of transversal logical gates is a finite discrete subgroup of the unitary group. Universality, which requires a dense subset of the unitary group, is therefore unattainable by transversal means alone in any finite-dimensional code that corrects local errors [1,3]. The Eastin-Knill theorem admits a natural reformulation in the language of covariant quantum codes, i.e. codes for which a continuous symmetry transformation on the logical system is implemented by a symmetry transformation on the physical system.

Table 1

Comparison of approximate Eastin-Knill bounds for covariant QEC against local erasure noise

Bound / construction	Symmetry group	Scaling of infidelity ε	Reference
Original no-go (exact)	Continuous $\{U(1), SU(2), \ldots\}$	$\varepsilon = 0$ is forbidden	[1]
Representation-theoretic bound	Compact Lie group	$\varepsilon \geq \Omega(1/n)$	[3]
Metrological bound (QFI)	$U(1)$	$\varepsilon \geq (\Delta H_L)^2 / (4F_S$	[4]
Thermodynamic code	$U(1)$	$\varepsilon \sim 1/n$ (erasure)	[4,5]
Single-shot min-entropy bound	Universal unitary	Necessary and sufficient	[6]

In this formulation the theorem states that exact covariant codes with respect to a continuous symmetry cannot correct local erasure exactly in finite dimensions [2,4]. In [4] recast covariant QEC as a quantum metrological protocol in which the estimation of an unknown rotation angle on the logical system is mapped to the estimation of the corresponding angle on the physical system, and derived analytic lower bounds on the worst-case entanglement infidelity ε in terms of the regularized symmetric-logarithmic-derivative quantum Fisher information of the noise channel [4]

$$\varepsilon \geq \ell_1\left(\frac{(\Delta H_L)^2}{4F_S^{reg}(N_S, H_S)}\right), \tag{1}$$

where $\ell_1(x) = \left(1+4x-\sqrt{(1+4x)}\right)/\left(2(1+4x)\right)$, $(\Delta H_L)^2$ is the variance of the logical Hamiltonian and $4F_S^{reg}$ is the regularized quantum Fisher information of the physical noise channel.

The bound holds whenever the Hamiltonian-in-Kraus-span condition is satisfied and is asymptotically saturated by a family of so-called thermodynamic codes for erasure noise [4,5]. An independent representation-theoretic approach in [3] established an approximate Eastin-Knill theorem of the form $\varepsilon \geq \Omega(1/n)$ for codes admitting a universal transversal action of a compact Lie group on n physical subsystems [3]. Since universality cannot be achieved by transversal gates alone in any single finite-dimensional code, fault-tolerant architectures combine transversal Clifford operations with additional resources that lift the gate set to universality. Three principal strategies are established in recent papers. First, magic-state distillation provides high-fidelity ancillary states that, together with transversal Clifford gates and gate teleportation, realize a non-Clifford gate such as the T gate; in conventional surface-code architectures this procedure has been estimated to account for a substantial fraction of the total qubit overhead [7,8]. Second, code switching transfers logical information between two codes whose transversal gate sets are mutually complementary, jointly spanning a universal set without resorting to distillation [9]. Third, concatenated and triorthogonal code constructions implement universal fault-tolerant gates by combining transversal operations at different concatenation levels with intermediate error correction [10]. Recent experimental work has demonstrated that these strategies are reaching the regime of practical fault tolerance. In 2025 high-fidelity logical magic states were prepared via code switching in the two-dimensional color code, with logical error rates comparable to or below the underlying two-qubit physical gate error rate, completing a universal fault-tolerant gate set together with previously demonstrated transversal Cliffords, state preparation and measurement [11].

Conclusions. The Eastin-Knill theorem constitutes one of the central structural results of fault-tolerant quantum computing. Its rigorous mathematical content that finite-dimensional codes correcting local errors admit only a discrete group of transversal logical unitaries has been substantially refined over the past five years through the development of approximate and covariant formulations, quantitative metrological bounds, and explicit code constructions that nearly saturate these bounds. The combined progress in theory and experimental realization of magic-state preparation and code switching indicates that the practical implications of the theorem, while fundamental, do not preclude scalable universal fault-tolerant quantum computation.

1. 1. Eastin B., Knill E. Restrictions on transversal encoded quantum gate sets. Physical Review Letters, 2009, vol. 102, no. 11, art. 110502.
2. 2. Hayden P., Nezami S., Popescu S., Salton G. Error correction of quantum reference frame information. PRX Quantum, 2021, vol. 2, art. 010326.
3. 3. Faist P., Nezami S., Albert V. V., Salton G., Pastawski F., Hayden P., Preskill J. Continuous symmetries and approximate quantum error correction. Physical Review X, 2020, vol. 10, art. 041018.
4. 4. Zhou S., Liu Z.-W., Jiang L. New perspectives on covariant quantum error correction. Quantum, 2021, vol. 5, art. 521.
5. 5. Kubica A., Demkowicz-Dobrzański R. Using quantum metrological bounds in quantum error correction: a simple proof of the approximate Eastin-Knill theorem. Physical Review Letters, 2021, vol. 126, art. 150503.
6. 6. Alexander R. A new approximate Eastin-Knill theorem. npj Quantum Information, 2025, vol. 11, art. 156.
7. 7. Bravyi S., Kitaev A. Universal quantum computation with ideal Clifford gates and noisy ancillas. Physical Review A, 2005, vol. 71, art. 022316.
8. 8. Litinski D. Magic state distillation: not as costly as you think. Quantum, 2019, vol. 3, art. 205.
9. 9. Yoder T. J., Takagi R., Chuang I. L. Universal fault-tolerant gates on concatenated stabilizer codes. Physical Review X, 2016, vol. 6, art. 031039.
10. 10. Bravyi S., Haah J. Magic-state distillation with low overhead. Physical Review A, 2012, vol. 86, art. 052329.
11. 11. Quantinuum collaboration. Experimental demonstration of high-fidelity logical magic states from code switching. arXiv:2506.14169, 2025.

Пояснюване AI/ML-виявлення аномалій у мікросервісних та мультихмарних середовищах

УДК 004.056.5:004.75:004.8

Віталій Криворучко[1]

Державний університет інформаційно-комунікаційних технологій,
[1]hamandes@gmail.com

У мікросервісних та мультихмарних середовищах засоби моніторингу формують великі обсяги телеметрії: метрики ресурсів, мережеві події, журнали доступу, HTTP-коди помилок та дані про взаємодію сервісів. Традиційний пороговий контроль часто виявляє лише факт відхилення і не пояснює, чому стан є ризиковим. Для кібербезпеки це ускладнює розмежування інциденту, деградації сервісу та звичайного коливання навантаження [1].

Мультихмарне середовище розглядається як сукупність сервісів, розгорнутих у різних хмарних доменах, регіонах або провайдерах. Метою роботи є розроблення підходу до пояснюваного AI/ML-виявлення аномалій,