Computer Science Review 61 (2026) 100942

Contents lists available at ScienceDirect

Computer Science Review

journal homepage: www.elsevier.com/locate/cosrev

Realization of measurement-based quantum computing model in fault-tolerant distributed quantum systems

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HIGHLIGHTS

- This work investigates distributed quantum computing systems, motivated by the limitations in achieving fault tolerance and scalability within monolithic architectures. It offers a systematic overview of circuit-based, measurement-based, and DQC approaches, outlining their development, fundamental principles, and recent advances.
- Highlights the importance of computational paradigms in addressing issues of scalability, fault tolerance and communication in distributed environments. This motivates a systematic comparison of CBQC and MBQC across five key dimensions: algorithmic structure, hardware heterogeneity, inter-node communication, fault tolerance, and resource utilization.
- Demonstrates the architectural advantages of MBQC for distributed quantum architectures, highlighting how its one-way, measurement-driven model reduces synchronization demands, supports heterogeneous hardware integration, and improves scalability, communication efficiency, and fault-tolerance behavior relative to CBQC.
- Presents a mathematically grounded case study of MBQC on trapped-ion platforms, illustrating how adaptive measurements, classical feedforward, and Pauli-frame tracking contribute to measurement-driven error mitigation within experimentally relevant cluster-state implementations.
- Examines emerging hardware, software, architectural, and industrial trends supporting MBQC-based distributed quantum computing. Identifies challenges in scalable cluster-state generation and classical feedforward latency, and outlines future directions focused on mitigating these limits and advancing secure and cloud-enabled distributed quantum services.

ARTICLE INFO

Keywords:
Distributed quantum computing (DQC)
Measurement-based quantum computation (MBQC)
Circuit-based quantum computation (CBQC)
Fault-tolerant quantum computing(FTQC)
Scalability

ABSTRACT

The constraints on achieving scalable and fault-tolerant quantum computation, together with the intrinsic architectural limitations of monolithic quantum processors, have motivated the exploration of Distributed Quantum Computing systems, where multiple quantum nodes collaborate through entanglement-assisted links to execute large-scale algorithms as a single logical computational platform. As different computational paradigms offer distinct trade-offs, identifying the most suitable architecture for scalable, efficient, and fault-tolerant quantum computing becomes crucial. This paper focuses on the two most widely adopted models, Circuit-Based and Measurement-Based Quantum Computing, and provides a novel and comprehensive comparison across five critical dimensions: algorithm design, hardware heterogeneity, inter-node communication, fault tolerance, and resource efficiency, establishing that MBQC offers distinct architectural and operational advantages for DQC. Building on this comparative framework, the work presents a mathematical perspective through a focused case study on MBQC, illustrating how adaptive measurements and classical feedforward can contribute to measurement-driven robustness against logical errors under realistic noise conditions. The paper concludes by outlining key challenges and future directions for the advancement of robust distributed quantum architectures.

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https://doi.org/10.1016/j.cosrev.2026.100942
Received 17 November 2025; Received in revised form 29 January 2026; Accepted 3 March 2026
Available online 11 March 2026
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Establishing and maintaining high-fidelity entanglement between spatially separated nodes is technologically demanding due to photon loss, decoherence, and limited transmission efficiency in quantum communication channels, particularly in photonic and hybrid architectures [39,40]. Synchronizing operations across distant modules introduces additional latency and control complexity, while entanglement links can serve as channels for error propagation, thereby degrading global system fidelity [37,41]. Current hardware platforms, whether based on superconducting qubits, trapped ions, or photonic systems, they do not yet possess the networking robustness and modular integration capabilities required for large-scale distributed operation [38]. As a result, existing DQC demonstrations are primarily limited to small-scale proof-of-concept systems rather than operational, fault-tolerant networks [42,43]. Furthermore, implementing QEC to achieve fault tolerance in distributed systems introduces additional complexity, including internode communication delays, synchronization errors, and hardware heterogeneity [34], while even local QEC remains susceptible to continuous coherent noise [24,44].

Although significant progress has been made in quantum hardware development, no existing platform has yet demonstrated a scalable, fault-tolerant quantum computer, nor an operational distributed quantum architecture capable of supporting logical qubits at scale. Major industrial leaders such as IBM have publicly outlined a long-term roadmap to build modular, error-corrected quantum systems by the early 2030s, relying on interconnected quantum processors linked via photonic channels and supported by quantum error correction codes [45]. Similarly, Google has set a strategic objective to realize a large-scale, error-corrected quantum computer within the next decade, focusing on surface code architectures and distributed logical qubit generation as foundational milestones toward scalable fault tolerance [46]. Other companies such as Quantinuum [47], IonQ [48], and PsiQuantum [49] are diligently developing modular trapped-ion and photonic platforms, with plans for networked quantum processors and cluster-state-based fault tolerance; however, these platforms remain in the pre-fault-tolerant regime and face substantial challenges related to error rates, resource overhead, and interconnect scalability. Thus, despite ambitious industrial roadmaps, current technologies have not yet overcome the fundamental barriers to achieving large-scale, fault-tolerant distributed quantum computation, underscoring the need for alternative architectures and algorithmic strategies that can minimize communication overhead, tolerate noise, and operate efficiently under realistic physical constraints.

In this context, the choice of computational model is not merely a theoretical consideration but a decisive factor in determining the scalability, fault tolerance, and practical viability of DQC architectures [50,51]. The adopted model governs how quantum information is generated, manipulated, and propagated across physically separated nodes, thereby directly influencing system-level attributes such as error accumulation, communication overhead, synchronization complexity, and the feasibility of modular integration. While a variety of quantum computational models have been explored in the literature including adiabatic quantum computation [52], topological approaches [53,54], and quantum walk-based models [55], circuit-based quantum computation (CBQC) and measurement-based quantum computation (MBQC) paradigms remain the two principal models underpinning both current hardware implementations and most algorithmic designs.

The CBQC model, which executes computation through unitary gate operations on qubits arranged in logical circuits, serves as the foundational paradigm for the majority of current quantum hardware platforms and algorithmic developments [56]. Owing to its resemblance to classical logic circuits and its compatibility with existing control architectures, CBQC has been the dominant model adopted by industrial quantum processors and large-scale research initiatives. However, when extended to distributed architectures, CBQC faces inherent limitations arising from its reliance on real-time coherent multi-qubit gate operations across spatially separated nodes, resulting in challenges such as inter-node synchronization delays, increased communication overhead, and heightened susceptibility to decoherence during long-range entangling operations [57]. In contrast, MBQC performs computation through adaptive single-qubit measurements on a pre-shared entangled resource state, eliminating the need for global coherent gate execution. The term resource state refers broadly to highly entangled quantum states prepared to enable measurement-based computation, while cluster states denote a specific and widely used subclass of such entangled resource states, including two-dimensional cluster states and three-dimensional (topological) cluster states. Due to its intrinsic support for locality, modularity, and measurement-driven adaptivity, MBQC is naturally aligned with the requirements of scalable and fault-tolerant DQC, where computation can proceed asynchronously with reduced communication demands [58,59]. Therefore, this paper undertakes a systematic comparison of CBQC and MBQC within the distributed paradigm, demonstrating both conceptually and mathematically how MBQC provides a more viable pathway toward building large-scale, fault-tolerant distributed quantum computers. To situate the scope, we introduce a taxonomy of distributed quantum computation paradigms (Fig. 2) and provide a structured comparison of the operational characteristics of CBQC and MBQC across key architectural and computational dimensions (Table 1).

1.1. Physical realization

The physical realization of scalable and fault-tolerant quantum computers constitutes a fundamental prerequisite for transitioning quantum computing from experimental prototypes to operational technologies capable of addressing real-world computational challenges [60,61]. Achieving such realization would enable the execution of classically intractable tasks in areas including quantum chemistry, materials design, combinatorial optimization, finance, and cryptography. A physically scalable architecture ensures that quantum resources can be expanded systematically without incurring exponential overheads, while fault tolerance preserves the integrity of quantum information throughout extended computations and communication processes [62]. Consequently, physical realizability has emerged as a central research focus across academic institutions, government laboratories, and industrial initiatives, reflecting its pivotal role in establishing reliable and interoperable quantum systems. The successful realization of scalable and fault-tolerant architectures will not only underpin practical quantum cloud infrastructures and high-fidelity quantum communication networks but also facilitate privacy preserving and distributed computation, thereby marking a decisive step toward the operational maturity of quantum technologies. This trajectory toward secure and distributed quantum information processing is exemplified by recent advances in quantum secure direct communication (QSDC) protocols, which demonstrate information-theoretic security across networked quantum nodes [63,64].

In this context, MBQC emerges as a promising model for distributed and secure quantum processing. Since MBQC is driven entirely by adaptive measurements on pre-shared entangled resources, it avoids the complexity of direct gate-based interactions between distant nodes [65]. This measurement-driven paradigm naturally integrates with Blind Quantum Computation (BQC), enabling clients to delegate quantum tasks to remote servers while keeping their data and algorithms confidential [66,67]. Therefore, the physical realization of MBQC within distributed architectures not only enhances scalability and fault tolerance but also enables inherently secure communication and privacy-preserving computation, positioning it as a viable foundation for future quantum networks and cloud-based quantum services [68,69].

1.2. Previous surveys and novelty of this work

Recent surveys have significantly contributed to the understanding of DQC by exploring architectural, networking, and system-integration factors. The work by Larasati et al. [70] presents one of the earliest

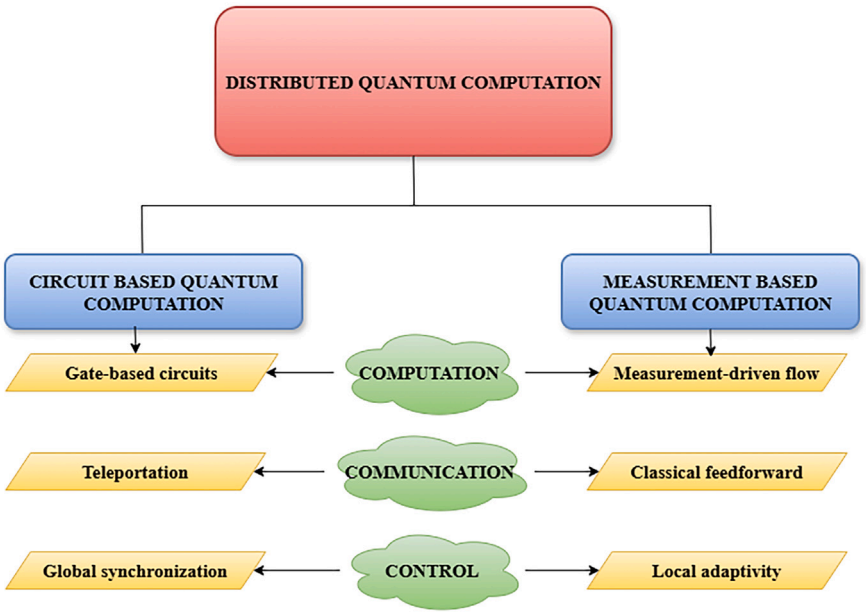


Fig. 2. Taxonomy of DQC showing how CBQC and MBQC handle computation, communication, and control.

Table 1
Fundamental working principles of CBQC and MBQC.

Aspect	Circuit based model	Measurement based model
How It Works	A sequence of unitary gates are applied to qubits, similar to programming a classical logic circuit.	A large entangled cluster state is prepared first, and computation proceeds through adaptive single-qubit measurements.
Primary Resource	An array of qubits with gates serving as the computational tool.	A pre-entangled cluster state that encodes the computational resource.
Control & Adaptivity	Deterministic execution following a fixed circuit.	Inherently probabilistic but made deterministic via feed-forward, where measurement outcomes guide subsequent measurement bases.
Decoherence	All qubits must maintain coherence for the full duration of the computation.	Only the measured qubits and their neighbors need to remain coherent temporarily, reducing overall decoherence demands.
Error Handling	Error correction is applied through dedicated quantum codes during gate operations.	Error resilience can be embedded in the entangled resource state, enabling topological error correction schemes.
Parallelism	Gate operations often require sequential execution, leading to deep circuits.	Many measurements can be performed simultaneously, offering natural parallelism.
Physical Implementation	Mature implementations in superconducting qubits, trapped ions, and other hardware platforms.	Naturally suited to photonic architectures, where generating large entangled states is more feasible than high-fidelity two-qubit gates.
Modularity	Architectures are typically monolithic and harder to partition into independent units.	Naturally modular, as different portions of the cluster state can encode independent sub-tasks.

taxonomies centered on fault tolerance in distributed systems, systematically organizing research across algorithmic, compilation, and networking layers to highlight the necessity for scalable and error-resilient architectures. Barral et al. [71] approach DQC from a high-performance computing perspective, presenting a layered analysis of distributed quantum systems ranging from single-QPU clusters to quantum farms, with emphasis on simulation frameworks and hardware–software co-design challenges. Similarly, the survey by Caleffi et al. [72] provides a foundational architectural viewpoint, introducing layered abstractions for DQC networks and highlighting critical bottlenecks such as synchronization and entanglement distribution delays. However, all three surveys inherently assume the CBQC paradigm and do not evaluate alternative computational models in terms of their impact on scalability or physical realizability.

In addition to these, existing MBQC reviews such as those by Briegel et al. [73] and Qin et al. [74] mainly emphasize the theoretical principles, graph-state development, and emerging application fields of MBQC. While these works introduce MBQC as a universal computation model and compare it conceptually with circuit-based methods, they do not address its role in distributed settings, nor do they investigate its intrinsic fault-tolerant properties or implications for network-level resource optimization. Similarly, studies on quantum internet architectures and evolutionary deployment pathways [75–79] discuss quantum communication and entanglement distribution but remain agnostic to the computational paradigm driving the processing at distributed nodes. A comprehensive comparison of existing survey literature is summarized in Table 2 to clearly delineate their scope and highlight the novel contributions of this work.

Table 2
Comparative overview of key surveys on distributed and measurement-based quantum computing.

Year	Authors	Focus area	Model	DQC	Fault tol.	Phys. real.	Key limitation
2009	Briegel et al. [73]	MBQC theory foundations	MBQC	No	No	No	Purely theoretical; no distributed scope.
2016	Van Meter et al. [77]	Scalability roadmap for distributed QC	CBQC	Yes	No	No	Architecture-focused; ignores MBQC and intrinsic fault tolerance.
2020	Cuomo et al. [76]	DQC architecture and networking	CBQC	Yes	Limited	Yes	Network-centric; lacks computational model comparison.
2020	Cacciapuoti et al. [78]	Quantum Internet and entanglement distribution	CBQC	Yes	No	No	Communication focus; computation aspects omitted.
2022	Loke et al. [75]	Transition from DQC to quantum internet	CBQC	Yes	No	No	Infrastructure-oriented; lacks MBQC evaluation.
2024	Qin et al. [74]	MBQC applications and advances	MBQC	No	No	No	Focused on MBQC theory; no distributed or scalable analysis.
2024	Tang et al. [80]	Hybrid quantum–classical DQC	CBQC	Yes	Limited	Yes	QEC-dependent; lacks MBQC integration.
2024	Caleffi et al. [72]	Comprehensive DQC architecture overview	CBQC	Yes	Limited	Yes	Model-agnostic; MBQC impact not analyzed.
2025	Larasati et al. [70]	Fault-tolerant DQC taxonomy	CBQC	Yes	Yes	Yes	Resource-heavy QEC; no intrinsic MBQC comparison.
2025	Barral et al. [71]	High-performance distributed architectures	CBQC	Yes	Limited	Yes	Performance-focused; omits MBQC scalability aspects.
2025	**This Work**	**CBQC–MBQC comparison for DQC**	**Both**	**Yes**	**Yes (Intrinsic)**	**Yes**	**Demonstrates MBQC's advantages in fault tolerance, resource efficiency, and physical realizability.**

This paper intends to address this gap by presenting the following key contributions:

- Performs an in-depth comparative analysis of CBQC and MBQC within the context of DQC across five critical dimensions: algorithm design, hardware heterogeneity, inter-node communication, fault tolerance, and resource efficiency and identify regimes in which MBQC provides architectural and systems-level advantages for distributed and fault-tolerant quantum environments.
- Develops a mathematically grounded case study of MBQC in trapped-ion systems, demonstrating how adaptive measurements and feedforward corrections contribute to measurement-driven error mitigation and state robustness within experimentally relevant cluster-state implementations.
- Provides theoretical insights into how MBQC's cluster state framework and modular entanglement structure can enhance scalability, interoperability, and physical realizability in distributed quantum architectures.

The remainder of this paper is structured as follows. Section 2 presents a comprehensive literature survey covering the evolution of quantum computing paradigms from CBQC to DQC and provides an in-depth discussion of MBQC as a promising model for distributed implementations. Section 3 outlines the theoretical prerequisites required to

Overview of the CBQC Model

Qubits form the fundamental units of computation in the CBQC paradigm, where information is represented in quantum states that can exist in coherent superpositions of classical bit values. A computation begins with the initialization of qubits, most commonly in the computational basis state $|0\rangle^{\otimes n}$. The quantum state of a single qubit is described as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \quad \text{where } |\alpha|^2 + |\beta|^2 = 1,$$

allowing superpositions of classical states. Multi-qubit registers extend this formalism via tensor products, enabling exponentially large Hilbert spaces.

Quantum Gates. Quantum gates correspond to unitary matrices that act reversibly on the state space. Common single-qubit gates include:

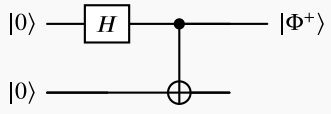
- *Hadamard* (H): $H|0\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$.
- *Pauli* (X, Y, Z): Bit-flip and phase-flip analogues.
- *Phase gate* (S) and T*-gate*: Controlled phase rotations.

Two-qubit gates, such as the *Controlled-NOT* (CNOT), enable entanglement. With $\{H, T, \text{CNOT}\}$, we obtain universality.

Circuit Representation. Quantum algorithms are expressed as circuits, where qubits are horizontal lines and gates are applied left to right. For example, the Bell state

$$|\Phi^+\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}},$$

is created by applying a Hadamard followed by a CNOT:



Superposition and Entanglement. CBQC exploits superposition for parallelism and entanglement for non-classical correlations. These enable speedups: Shor's algorithm uses interference for factoring, while Grover's algorithm applies amplitude amplification for search.

Measurement and Outputs. At the end, qubits are measured in the computational basis, collapsing the state. Classical post-processing yields the algorithmic result.

understand the concept of fault tolerance in quantum systems. Section 4 provides a comparative analysis of CBQC and MBQC across five critical dimensions to assess their suitability within DQC environments. Section 5 provides a mathematically based case study of MBQC in trapped-ion systems, demonstrating how it facilitates measurement-based error reduction and strengthens the resilience of quantum states. Finally, Section 6 discusses emerging trends in distributed and hybrid quantum architectures, including advances in hardware, software, compiler design, and industrial implementations and concludes the paper with open challenges and future research directions.

2. Literature survey

Quantum computing has progressed through multiple paradigms, where the dominant CBQC established the foundation for algorithm design and hardware development, and DQC extends this model across networked quantum processors. More recently, MBQC has emerged as a resource-driven paradigm that offers natural advantages for modular and distributed architectures. This section surveys the conceptual evolution and foundational works of these paradigms, outlining their interconnections and the motivation for transitioning toward MBQC as a distributed model.

2.1. Circuit based quantum computing

CBQC remains the canonical framework for quantum computing, where qubits initialized in the computational basis undergo a series of unitary gate operations followed by projective measurements. A brief overview of the CBQC paradigm is provided in the box enclosed. This framework was rigorously established by Yao in 1993 [81], building upon Deutsch's concept of universal quantum computation in 1985 [82]. The power of CBQC was quickly illustrated by landmark algorithms, including Shor's factoring and discrete logarithm algorithms in 1994 [13] and Grover's unstructured search algorithm in 1996 [83], which demonstrated asymptotic speedups and catalyzed the development of hardware and compilation stacks. Recent development in CBQC hardware feature IBM's 127-qubit Eagle processor with reduced crosstalk [84], Google's Sycamore chip demonstrating quantum supremacy [6], and newer platforms such as Microsoft's Majorana-based chip [85], Amazon's Ocelot [86], and Quantinuum's H2 system [87]. In terms of software, tool such as Qiskit [88], Cirq [89], and TensorFlow Quantum [90] have matured to support scalable circuit design and efficient compilation [91].

As quantum algorithms grew in scope, the issue of fault tolerance became central. In his influential article, Preskill laid out the theoretical foundations for overcoming noise and decoherence, which established the threshold theorem and formalized how reliable quantum computation can be achieved if the physical error rate lies below a certain constant threshold [92]. In this context, a substantial body of work has focused on developing fault tolerant circuit-based architectures, leveraging surface codes [34,93], lattice surgery [94,95], and magic state distillation [35,96] to mitigate noise and facilitate large-scale algorithms. More recently, low-density parity-check (LDPC) codes [97,98] have emerged as a promising alternative offering constant-rate, high-threshold fault-tolerant architectures, although their practical decoding overhead and hardware connectivity constraints remain challenging. Notably, Google reported distance-3 through distance-7 surface-code logical qubits that surpassed the break-even point where logical error rates were lower than those of physical qubits [99], while Quantinuum demonstrated real-time decoding and logical entangling with color codes, achieving logical fidelity exceeding physical performance in a trapped-ion system [100].

However, as hardware scales upward, monolithic circuit-based systems face practical limitations in qubit connectivity, control crosstalk, and cryogenic resource overheads. These constraints have driven the exploration of distributed implementations of CBQC, setting the stage for the emergence of DQC architectures.

2.2. Distributed quantum computing

DQC has emerged as a compelling solution to the architectural bottlenecks in scalability and fault-tolerance faced by monolithic quantum architectures. Instead of relying on a single large processor, it interconnects spatially separated quantum processing units (QPUs) through quantum and classical communication channels, enabling modular architectures that divide computations across smaller and more manageable subsystems. The earliest theoretical explorations date back to the late 1990s. Gottesman and Chuang introduced the teleportation-based model, showing that entanglement and classical communication could substitute for direct qubit–qubit interactions in implementing non-local gates [101]. Shortly after, Cirac et al. extended this idea by proposing protocols for distributed two-qubit gates over noisy channels, demonstrating that entanglement distribution with purification enables high-fidelity CNOT operations and offers greater robustness than direct quantum state transmission [42]. Yimsiriwattana and Lomonaco [102] extended these principles into the algorithmic realm by implementing a distributed version of Shor's factoring algorithm. This work was among the earliest to show that scalable, networked quantum processors could collectively execute algorithms beyond the reach of a single device.

These foundational works have since inspired a decade of research into practical architectures for DQC. Experimental advances in ion-trap systems have demonstrated remote entanglement generation between spatially separated modules via photonic interference, as highlighted in the Modular Universal Scalable Ion-trap Quantum Computer (MUSIQC), which achieved fidelities exceeding 90% [38], and in the cell-based scalable and fault-tolerant architecture, where remote entanglement links are purified and multiplexed to mitigate photon loss [37]. Photonic approaches have demonstrated scalable routing protocols capable of constructing large-scale graph states, including cluster states as a specific subclass, across hundreds of nodes under realistic photon-loss conditions [103,104]. Solid-state NV centers have achieved heralded entanglement over 1.3 km of optical fiber at Hz-level rates, highlighting their advantage for long-distance networking [105]. Superconducting processors, although restricted to short centimeter-scale connections, have achieved chip-to-chip entanglement through microwave photons with fidelities near 79% [106]. Collectively, these efforts confirm that modularity is experimentally viable, with each platform offering complementary strengths. This diversity underscores the central insight from early theoretical proposals that modularity is not optional but rather essential for realizing fault tolerant and scalable quantum computation.

Early architectural blueprints for DQC sought to extend the CBQC model to distributed settings. However, this approach has proven to be highly challenging [37,107]. The survey by Caleffi et al. [72] outlines how CBQC struggles in distributed settings due to the need for tightly coordinated gate operations, rapid classical feedback, and strict timing control across quantum nodes. These factors are often infeasible in large-scale or heterogeneous quantum networks. Complementing this, Barral et al. [71] provide a layered perspective on DQC development, classifying simulation tools into hardware, protocol, and application oriented levels. While discussing architectures from single QPUs to wide-area quantum farms, they emphasize the physical-layer constraints and latency issues inherent to CBQC. Together, these surveys underscore the limitations of CBQC in distributed environments and motivate the exploration of alternative paradigms, such as MBQC, that naturally decouple entanglement generation from computation.

2.3. Measurement based quantum computing

MBQC provides an alternative model to the circuit-based paradigm, where computation proceeds not through sequential gate applications but via adaptive single-qubit measurements on a pre-prepared entangled graph state resource, typically instantiated as a cluster state for universal quantum computation. In this framework, computation unfolds in three primary stages: **(1)** generation of a *cluster state*, **(2)** *adaptive local measurements* guided by classical feed-forward, and **(3)** application or

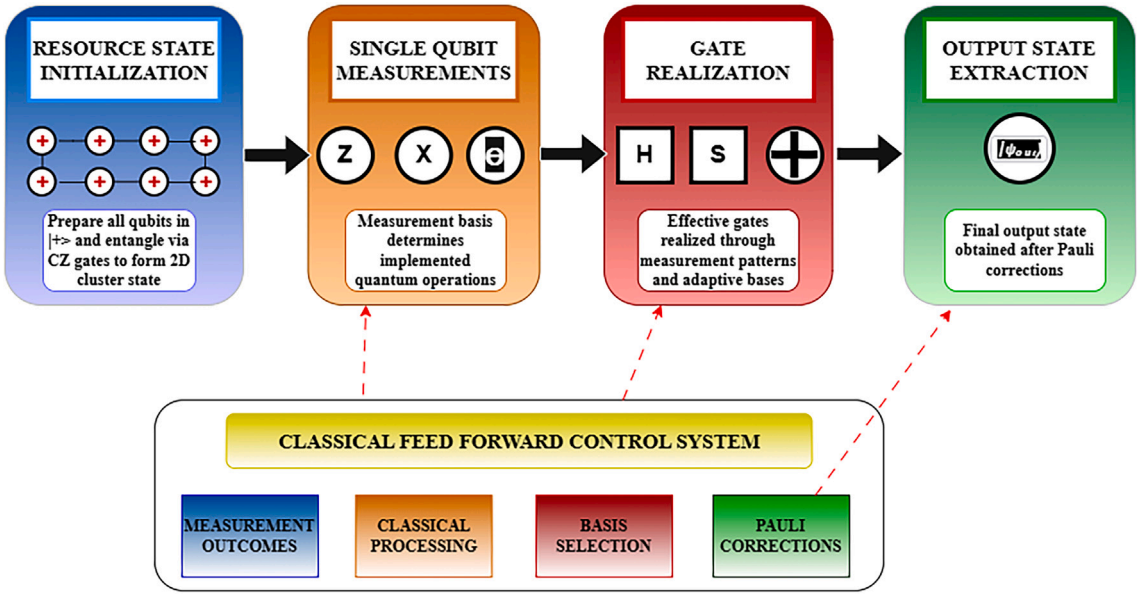


Fig. 3. Block diagram of MBQC.

tracking of *Pauli corrections* to yield the deterministic output. Fig. 3 illustrates this workflow, beginning with resource state preparation and progressing through adaptive measurements to yield the final output state.

In the first stage, each qubit is initialized in the superposition state

$$|+\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle),$$

and entanglement is established through controlled-Z (CZ) operations between qubits connected by the edges of an underlying graph $G = (V, E)$, producing the cluster state

$$|G\rangle = \prod_{(i,j)\in E} CZ_{ij} \bigotimes_{v\in V} |+\rangle_v.$$

Subsequent computation proceeds through single-qubit projective measurements in the equatorial basis

$$B(\phi_j) = \{|+_{\phi_j}\rangle, |-_{\phi_j}\rangle\}, \quad |\pm_{\phi_j}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle \pm e^{i\phi_j}|1\rangle\right),$$

where the measurement angles ϕ_j specify the logical operation being executed. The intrinsic randomness of measurement outcomes $s_j \in \{0, 1\}$ induces Pauli byproduct operators, particularly X and Z corrections, which are compensated through adaptive modification of future measurement bases, $\phi \mapsto (-1)^s\phi + s\pi$. Classical feed-forward of these outcomes ensures that, despite probabilistic measurements, the overall computation remains deterministic. The logical action of the entire measurement pattern can be described as

$$|\psi_{\text{out}}\rangle = P(\{s_j\})\, U\, |\psi_{\text{in}}\rangle,$$

where U is the intended unitary transformation and $P(\{s_j\})$ is the cumulative Pauli correction based on measurement outcomes.

This "one-way" model, first introduced by Raussendorf and Briegel [59], shifts the quantum complexity from dynamic multi-qubit gates to one entanglement-preparation step, enabling computation to proceed through simpler, local operations. The entangled resource is gradually consumed as measurements progress, with classical controlmaintaining deterministic evolution. Raussendorf, Browne, and Briegel [108] later proved the universality of this scheme by demonstrating that arbitrary unitary operations can be realized through suitable measurement patterns in cluster states, thereby establishing MBQC as computationally equivalent to the circuit model. These developments collectively transformed MBQC from a conceptual alternative into a scalable, resource-efficient, and fault-tolerant computational model. In the following sections, we compare CBQC and MBQC, highlighting MBQC's advantages for modular and distributed architectures, and subsequently discuss how fault-tolerant properties are realized within the MBQC paradigm.

Table 3 synthesizes the most recent research efforts aimed at enhancing scalability and fault tolerance in emerging quantum computing architectures, with an emphasis on distributed and measurement-based paradigms.

3. Prerequisites

In a fault-tolerant quantum computing (FTQC) framework, we consider a system governed by the Schrödinger equation with controllable classical signals $f_k(t)$, $k = 1, 2, \ldots, m$. Let $\{x_1, x_2, \ldots, x_r\}$ be a set of observables such that, for each observable x_m, there exists a corresponding reference function $\psi_m^0(t)$. We therefore solve the controlled Schrödinger equation

$$i\frac{\partial}{\partial t}\psi(t) = \left(H_0 + \varepsilon \sum_{k=1}^{m} f_k(t)V_k\right)\psi(t), \tag{1}$$

with the control functions $f_k(t)$ chosen over a time interval $[0, T]$ such that the tracking functional

$$\sum_{m=1}^{r} \int_0^T \left(\langle\psi(t), x_m\psi(t)\rangle - \psi_m^0(t)\right)^2 dt \tag{2}$$

is minimized. This captures the objective of selecting controls that align the system's evolution with desired observable trajectories.

This problem can be modified to incorporate the quantum measurement postulate. Suppose the FTQC system begins in some initial state $|\psi_0\rangle$ and evolves freely up to time t_1 according to Schrödinger dynamics. The cumulative error energy up to time t_1 is defined as

$$\int_0^{t_1} \|\psi(t) - U(t, 0)\psi(0)\|^2\, dt, \tag{3}$$

Table 3
Recent developments in distributed, circuit-based, and measurement-based quantum computation.

Author	Year	Scope	Technique used
D. Schwerdt et al. [109]	2024	CBQC architecture (scaling)	Scalable trapped-ion architecture proposals (reconfigurable cells, optical tweezers) enabling long chains and modularization relevant to distributed deployment.
W. Song et al. [110]	2024	MBQC / Photonic FBQC (fault tolerance)	Encoded-fusion MBQC, encoded fusion measurements and fault-tolerant fusion-based photonic schemes reducing loss sensitivity.
D. Main et al. [111]	2025	CBQC in DQC (experimental)	Experimental distributed quantum computing across a photonic optical link between trapped-ion modules, heralded remote entanglement and gate teleportation.
Y. van Montfort, S. de Bone, D. Elkouss [58]	2025	MBQC, FT, DQC	Construction of fault-tolerant MBQC resource structures for networked computation; network-aware lattice design and threshold estimates.
L. Oleynik, J. U. Rehman, S. Koudia, S. Chatzinotas [112]	2025	DQC (entanglement distribution)	Analysis and protocol design for entanglement distribution in lossy networks; resource budgeting and distillation strategies.
M. L. Chan et al. [113]	2025	MBQC / Fusion-based photonics	Tailoring fusion-based photonic architectures to quantum-emitter noise models, architectural design and threshold analysis for photonic MBQC.

where the propagator $U(t,s)$ depends functionally on the control signals $f_k(t)$ and satisfies

$$i\frac{d}{dt}U(t,s)=\left(H_0+\varepsilon\sum_k f_k(t)V_k\right)U(t,s),\qquad t\geq s. \tag{4}$$

At time t_1, a measurement of an observable X is performed. Let the system collapse to the eigenstate $|\alpha_1(t_1)\rangle$ of X. The subsequent evolution from t_1 to a later time t_2 is given by

$$U(t_2,t_1)|\alpha_1\rangle, \tag{5}$$

and the error energy on this interval is

$$\int_{t_1}^{t_2}\left\|\psi_q(t)-U(t,t_1)|\alpha_1\rangle\right\|^2 dt. \tag{6}$$

At time t_2, another measurement of X is performed, yielding an outcome corresponding to the eigenstate $|\alpha_2\rangle$. The system then evolves as

$$U(t,t_2)|\alpha_2\rangle, \tag{7}$$

until the next measurement time t_3. Repeating this process at discrete times

$$t_1<t_2<\cdots<t_N, \tag{8}$$

we obtain a sequence of measurement outcomes

$$\alpha_1,\alpha_2,\ldots,\alpha_N. \tag{9}$$

The total wavefunction tracking error energy across all measurement intervals is then

$$E_T=\sum_{k=0}^{N-1}\int_{t_k}^{t_{k+1}}\left\|\psi_q(t)-U(t,t_k)\psi(t_k)\right\|^2 dt. \tag{10}$$

Density Matrix Formulation

If a measurement of X is performed at time t_k but the measurement outcome is not recorded, then a density-matrix description is required. If the pre-measurement state is $\rho(t_k^-)$, the post-measurement state becomes

$$\rho(t_k^+)=\sum_{k=1}^{r}e_k\langle e_k|\rho|e_k\rangle e_k, \tag{11}$$

where

$$X=\sum_k\lambda_k e_k\langle e_k| \tag{12}$$

is the spectral decomposition of the observable X.

The expected measurement outcome is

$$\mathrm{Tr}(\rho X)=\sum_k\langle e_k|\rho|e_k\rangle\langle e_k|X|e_k\rangle=\sum_k e_k\langle e_k|\rho|e_k\rangle. \tag{13}$$

We note that

$$\mathrm{Tr}(\rho X)=d_s\,\mathrm{Tr}(\rho_t X). \tag{14}$$

In this density-matrix picture, the full error energy is expressed as

$$E_T=\sum_{k=0}^{N-1}\int_{t_k}^{t_{k+1}}\left\|\rho_d(t)-\rho(t)\right\|_d^2 dt, \tag{15}$$

where

$$\rho(t)=U(t,t_k)\rho(t_k)U(t,t_k)^*,\qquad t_k<t<t_{k+1}, \tag{16}$$

and the post-measurement density operator is

$$\rho(t_k^+)=\sum_m|e_m\rangle\langle e_m|\,\rho(t_k^-)\,|e_m\rangle\langle e_m|. \tag{17}$$

4. Framework and comparative analysis

The foundational taxonomy and operational distinctions between circuit-based and measurement-based paradigms were outlined in Section 1. Building on this groundwork, this section establishes a unified framework for comparing their scalability, fault tolerance, and suitability for distributed architectures. We identify five key dimensions: algorithm design, hardware heterogeneity, inter-node communication, fault tolerance, and resource efficiency, that collectively determine the scalability and robustness of quantum computing systems in distributed settings. These dimensions, widely adopted in recent evaluations [5,114], provide a structured basis for assessing how CBQC and MBQC support reliable large-scale quantum computation. The corresponding evaluation metrics are summarized in Table 4, along with the summary of comparative analysis that follows, highlighting CBQC's limitations in distributed contexts alongside the advantages of MBQC for scalable, fault tolerant architectures. The table summarizes these distinctions based on estimates that are derived from asymptotic analyses and architectural projections reported in previous works, assuming high-fidelity entanglement generation and fault-tolerant operation, as commonly adopted in comparative architectural studies rather than platform-specific experimental benchmarks.

4.1. Algorithm portability

The advancements in quantum algorithm design have established powerful new computational paradigms; however, distributed execution of such algorithms continues to face a primary challenge.

Table 4
Key evaluation metric and comparative summary for distributed CBQC and MBQC.

Dimension	Metric definition	CBQC	MBQC
Algorithm Design	Logical depth (D_L); non-local operation ratio (R_{NL})	Deep sequential circuits; high R_{NL} due to repeated remote gates and teleportation [102,118]	Parallel measurement layers; non-locality absorbed into resource states, reducing D_L and R_{NL} [59]
Hardware Heterogeneity	Inter-platform compatibility index (I_C)	Platform-specific gate sets and calibration reduce interoperability across nodes [120]	Model-level hardware agnosticism via measurement universality; physical resource fidelity remains platform-dependent
Inter-Node Communication	Entanglement rate (Γ_E); synchronization latency (L_{sync})	High Bell-pair consumption per remote gate; strict quantum-level synchronization [37]	Entanglement front-loaded into cluster states; runtime communication is classical feed-forward
Fault Tolerance	Logical error rate (ε_L); error threshold (T_{err})	Surface/concatenated codes with thresholds $\sim 10^{-3}$–10^{-2}; degraded by link noise [34,121]	Measurement-driven error suppression embedded in resource states; comparable thresholds under idealized conditions
Resource Efficiency	Qubit overhead (O_Q)	Large persistent code patches; high physical-qubit overhead for distributed execution [122]	Resource-state consumption model; projections suggest lower O_Q, contingent on efficient cluster generation

Quantum algorithms must exhibit native compatibility with distributed environments, wherein perfectly distributable algorithms comprise weakly interacting modules that execute independently with minimal inter-node dependencies [115]. Algorithm portability quantifies this property through two key metrics, D_L and R_{NL}, where low D_L and R_{NL} suggest higher portability, reflecting minimal communication overhead and efficient parallel execution across distributed processors.

For CBQC, executing distributed tasks poses difficulties because many foundational algorithms, such as the Quantum Fourier Transform (QFT) and the Harrow–Hassidim–Lloyd (HHL), rely on global connectivity and deep circuit structures [116,117]. The QFT requires global entangling gates, resulting in a high R_{NL} and significant communication overhead when distributed across nodes. Studies on distributed implementations of Shor's factoring algorithm have shown that communication complexity scales as $\mathcal{O}((\log N)^2)$ for an N-bit integer [102], while each non-local controlled-U operation consumes one maximally entangled pair, further increasing R_{NL} and D_L [118]. Consequently, both D_L and R_{NL} rise sharply with problem size, limiting scalability and algorithm portability in CBQC. Whereas, MBQC provides superior portability in distributed architectures. Computation proceeds through single qubit measurements on a pre-entangled cluster state, with inter-node communication limited to cluster distribution and classical feed-forward rather than repeated remote gate teleportations [59]. Non-local gates can thus be simulated via local measurements and feed-forward, effectively reducing D_L and R_{NL}. Moreover, experimental demonstrations of photonic cluster states exceeding 10,000 modes have confirmed MBQC's scalability and communication efficiency over CBQC in DQC [119].

4.2. Hardware heterogeneity and architectural considerations

Hardware heterogeneity in DQC allows different modules to exploit the strengths of distinct quantum platforms, such as superconducting qubits for fast gates, trapped ions for long coherence, and photonics for efficient communication. This interoperability can be assessed using I_C, with higher I_C indicating smoother cross-platform coordination.

In the CBQC paradigm, hardware heterogeneity poses significant architectural and compilation challenges, as different quantum platforms employ distinct native gate sets, connectivity patterns, and control fidelities, reducing I_C. For example, even within superconducting qubit systems, IBM's transmon processors use cross-resonance CX gates, whereas Google's Sycamore employs $fSim$-based entangling gates, each requiring unique calibration strategies [7,120]. Such disparities lower the I_C, since extensive gate translation and recompilation are needed to enable cross-device execution. In contrast, MBQC exhibits higher I_C at the computational model level, as its universality enables the realization of arbitrary logical operations through appropriate measurement bases and adaptive corrections, largely decoupling logical gate synthesis from the native gate set of the underlying hardware. In this sense, MBQC can be regarded as architecturally hardware-agnostic, even though the physical fidelity of the required entangled resource states remains platform-dependent.

At the physical layer, however, the preparation and scalability of cluster-state resources are strongly influenced by platform-specific constraints. In photonic implementations, photon loss, probabilistic entangling or fusion operations, and finite detector efficiencies impose substantial overheads and limit achievable cluster sizes. Conversely, trapped-ion platforms support high-fidelity, deterministic entangling gates that enable precise cluster-state generation within a module, but inter-module entanglement distribution is typically slow, heralded, and constrained by photonic coupling efficiencies. These trade-offs directly influence the achievable fidelity of the cluster state and, in turn, the practical scalability of MBQC across various hardware platforms. Experiments on hybrid superconducting–photonic systems [106] and extensive photonic cluster states [119] demonstrate the adaptability and the physical challenges of MBQC in heterogeneous architectures.

4.3. Inter-node communication and synchronization

Inter-node communication defines how efficiently quantum information is exchanged or correlated across spatially separated modules. Quantum states are delicate and cannot be replicated because of the no-cloning theorem, so direct qubit transmission via optical or fiber connections experiences photon loss and decoherence. Hence, DQC systems rely on entanglement distribution between nodes, enabling teleportation-based protocols such as TeleData [123] and TeleGate [124,125] that emulate non-local gates through local operations and classical signaling [126]. This dimension can be quantified using two metrics, Γ_E and L_{sync}, where high Γ_E and low L_{sync} reflect efficient and stable inter-node communication, both critical for scalable DQC.

In practice, the generation and maintenance of high-fidelity inter-node entanglement introduce nontrivial overheads that impact both paradigms. In photonic and optically mediated platforms, photon loss, probabilistic entanglement generation, finite quantum-memory coherence times, and entanglement purification protocols substantially reduce the effective entanglement rate and increase latency. These effects limit the achievable values of Γ_E and introduce additional buffering and storage requirements, particularly when large-scale entangled resource states must be distributed across distant nodes.

In the CBQC paradigm, distributed gate execution requires frequent non-local interactions that depend on high-fidelity entanglement and sub-nanosecond synchronization, making scalability difficult [38]. Experimental and simulated studies report that Γ_E drop sharply with distance, often below 10^3 pairs/s for optical links exceeding 50 km, while L_{sync} increase due to classical signaling and calibration delays [78]. In contrast, MBQC mitigates these limitations through pre-shared cluster states that encapsulate the entanglement structure in advance, at the cost of increased upfront entanglement-generation and storage overheads [37]. Once distributed, computation proceeds via local measurements and classical feed-forward, eliminating the need for continuous

quantum-level synchronization. Consequently, when resource states can be generated and buffered successfully, MBQC can achieve higher effective Γ_E at runtime, since entanglement generation can be decoupled from logical operations, and lower L_{sync} during computation.

4.4. Fault tolerance

Fault tolerance quantifies the system's ability to maintain computational integrity under decoherence, gate errors, and measurement noise. It can be evaluated through ε_L and T_{err}, lower ε_L and higher T_{err} indicate more resilient architectures. In distributed environments, achieving these conditions is challenging due to heterogeneous noise, lossy quantum channels, and synchronization imperfections across nodes.

It is important to note that the fault-tolerance thresholds reported for both CBQC and MBQC typically assume sufficiently high-fidelity entanglement resources. In distributed and photonic implementations, imperfect entanglement generation, photon loss, and finite coherence times introduce correlated errors that effectively lower these thresholds and increase physical resource requirements. These overheads must be amortized through entanglement purification, redundancy, or probabilistic retry strategies, which can significantly impact practical scalability.

In CBQC, error resilience is primarily achieved through surface and concatenated codes, which achieves an error threshold of approximately $T_{err} \approx 1\%$ under depolarizing noise, but it requires a large number of physical qubits to encode a single logical qubit [34,36]. However, in distributed extensions, teleportation-based entanglement and synchronization overheads significantly lower thresholds. Van Meter et al. and Iolius et al. showed that even modest entanglement infidelity ($< 2\%$) or link asymmetry can reduce effective thresholds to 10^{-3}–10^{-4}, depending on inter-node latency and photon loss [121,126]. Furthermore, distributed surface-code implementations require non-local stabilizer checks across nodes, inflating qubit overheads by nearly an order of magnitude.

MBQC integrates fault-tolerance mechanisms directly into the structure of its entangled resource states, shifting much of the fault-tolerance burden from active gate-level correction to measurement-driven error suppression and classical post-processing. This is realized through three-dimensional cluster states, most prominently the Raussendorf Harrington Goyal (RHG) lattice, where the additional spatial dimension represents the temporal evolution of computation. MBQC attains topological fault tolerance by incorporating surface codes into these cluster states, relying solely on local measurements and classical post-processing [127,128]. The resulting 3D codes show error thresholds of around $T_{\text{err}} \approx 0.7\%$–$1\%$, similar to conventional surface codes, while preserving logical stability despite qubit loss rates beneath 5% and moderate measurement errors. Recent distributed MBQC models employ modular cluster lattices and entanglement swapping between subclusters, achieving stable logical error rates below 10^{-4} for link fidelities above 0.98 [69]. As error correction in MBQC relies on classical feed-forward rather than real-time gate feedback, it tolerates asynchronous operations and reduces synchronization overhead, rendering it particularly well suited to modular and asynchronous distributed architectures, provided that the cost of resource-state preparation can be managed.

4.5. Resource utilization and qubit scaling

Resource efficiency can be quantified using O_q, defined as the total number of physical qubits required per logical qubit, including those dedicated to error correction, entanglement distribution, and inter-node communication. Lower O_q values indicate more scalable and hardware-efficient architectures.

In CBQC, distributed nodes must maintain large surface-code patches or equivalent fault-tolerant structures to support logical operations. Each node also bears the cost of generating and purifying entanglement for non-local gates, leading to substantial resource inflation. Nickerson et al. [37] demonstrated that inter-cell networking with surface codes requires several hundred physical qubits per logical qubit once photonic link losses and purification are considered. Large-scale algorithmic analyses reinforce this challenge: Gidney and Ekerå estimated that factoring a 2048-bit RSA number using surface-code-based CBQC would require approximately 2×10^7 physical qubits [122], while Beverland et al. showed that distributed and heterogeneous fault-tolerant architectures could further increase O_q due to interconnect redundancy and synchronization demands [129]. Recent demonstrations of practical quantum-inspired factorization, including the successful factoring of RSA-100 and observed algorithmic speed-ups, highlight alternative hybrid approaches that may alleviate some resource pressures [130,131]. Thus, although CBQC provides well-established frameworks for resource estimation, its distributed realization incurs significant physical and operational overhead.

Whereas, MBQC inherently minimizes qubit overhead by transferring circuit complexity into the preparation and distribution of entangled resource states. A notable variant of MBQC is Fusion-Based Quantum Computing (FBQC), which adopts the same measurement-driven paradigm but constructs large-scale cluster networks through entanglement fusion of smaller photonic resource states. Recent FBQC approaches demonstrate how small, constant-size photonic resource states can be fused into large-scale cluster networks, reducing per-node hardware requirements by orders of magnitude [132,133]. In these architectures, physical qubits (photons) are consumed during fusion and immediately discarded, removing the need for long-lived quantum memories and minimizing O_q.

These advantages, however, come with non-negligible resource-generation costs. In photonic MBQC and FBQC platforms, probabilistic fusion operations, photon loss, and finite detector efficiency require substantial redundancy, leading to increased raw resource consumption before a usable large-scale cluster is realized. Similarly, limited quantum-memory coherence can impose strict timing constraints on cluster assembly and consumption.

Furthermore, modular photonic and neutral-atom MBQC designs enable node downscaling, with each module limited to a few qubits while scalability is achieved through networked fusions and routing [75,134]. These strategies indicate that while MBQC does not eliminate entanglement-generation overheads, it localizes and front-loads them, allowing logical execution to proceed with reduced synchronization, memory, and control demands.

Mini-case study: distributed algorithms under CBQC and MBQC

To illustrate the comparative behaviour of circuit-based and measurement-based paradigms in DQC, we examine the execution of Shor's algorithm, a canonical benchmark for large-scale quantum factoring. Its modular-exponentiation and QFT stages make it highly sensitive to inter-node communication, synchronization overhead, and fault-tolerance overhead.

In the CBQC model, distributed modular exponentiation requires repeated remote entanglement and teleportation between nodes, incurring a communication cost on the order of 10^3 Bell pairs per remote gate in common resource estimates [37]. Furthermore, state-of-the-art fault-tolerant counts for factoring a 2048-bit integer suggest physical qubit counts exceeding 2×10^7 logical–physical qubit overheads [122]. The large qubit-count, deep logical circuit, and heavy inter-node synchronization combine to create significant scaling and modularity hurdles.

By contrast, an MBQC-based implementation can leverage pre-shared cluster states and locality-preserving measurement sequences to reduce both communication and synchronization overhead. Fusion-based MBQC proposals and resource-state analyzes [135] suggest order of-magnitude reductions in qubit overhead under idealized architectural assumptions, along with projected reductions in logical depth of the order of 30–40%, while maintaining fault-tolerance thresholds that are comparable to circuit-based approaches. As summarized in Table 5,

Table 5
Comparison of distributed shor's algorithm under CBQC vs. MBQC.

Dimension	CBQC	MBQC	Trend
Logical Depth	High, sequential modular exponentiation	Projected ∼30–40% lower via parallel measurement layers [135]	↓ Reduced
Communication Overhead	$\sim 10^3$ Bell pairs per gate [37]	Pre-shared cluster links, minimal teleportation	↓ Strongly reduced
Fault Tolerance	Surface-code thresholds $\sim 10^{-3}$	Comparable topological thresholds	≈ Comparable
Qubit Overhead	$> 2 \times 10^7$ (for 2048-bit) [122]	$\sim 10^6$ (projected, architecture-dependent) [135]	↓ Lower
Scalability	Synchronization-limited, link-dependent	Link-asynchronous, modular architecture	↑ Improved

these results are derived from resource-estimation and architectural analyses, rather than end-to-end experimental realizations.

This comparison emphasizes that for large-scale, modular and fault-tolerant workloads such as Shor's algorithm, MBQC offers system-level architectural advantages in a distributed setting. In particular, it reduces communication and synchronization burdens, enables effective downscaling of qubit resources through optimized entangled-state design, and simultaneously preserves logical universality and fault resilience.

Although VQE is more NISQ-oriented and shallow in depth, MBQC can still provide benefits, albeit more modest ones. For distributed VQE scenarios, recent work such as Shuffle-QUDIO [136] demonstrates how communication frequency can be reduced and convergence improved via adaptive partitioning and distributed sub-ansätze. MBQC-inspired architectures [137] propose measurement-based ansätze that translate VQE workloads into resource-state and measurement frameworks, potentially lowering circuit depth or enabling better parallelism. Thus, while the advantage of MBQC is not as pronounced as in Shor's case, it remains a promising pathway for improved resource efficiency and distributed execution in hybrid quantum-classical algorithms.

5. Case study: measurement-based quantum computation with trapped-ion cluster-state generation and initial-state estimation

The purpose of this section is to present a focused case study illustrating how MBQC can be instantiated on trapped-ion platforms through experimentally relevant cluster-state generation and state-estimation techniques. It contextualizes representative mathematical tools and experimental considerations within the broader review narrative on MBQC based distributed and fault-tolerant quantum computing.

This case study particularly emphasizes the subsequent elements:

1. Experimental generation of one- and two-dimensional cluster states in strings of $^{40}Ca^+$ ions confined in a linear Paul trap.
2. Demonstrations of universal gate operations realized through MBQC measurement patterns.
3. Development of cluster-state codewords applicable for QEC.
4. A perturbative approach for evaluating the initial quantum state during continuous measurement defined by Lindblad dynamics, included as a representative example of state characterization techniques compatible with MBQC.

Taken together, these components establish a mathematically grounded and experimentally relevant perspective on MBQC in trapped-ion platforms, encompassing cluster-state generation, state characterization, and measurement-driven error mitigation. In the MBQC model, global quantum computation is enabled through the preparation of highly entangled multipartite cluster states, followed by adaptive projective single-qubit measurements with classical feedforward. Recent advances in scalable trapped-ion control and high fidelity entangling operations have made the generation of large cluster states increasingly feasible, thereby supporting the practical realization of MBQC under realistic noise conditions. Within this framework, fault-tolerance oriented considerations naturally arise through the interplay between measurement adaptivity, open-system dynamics, and state estimation. The mathematical formulations presented in this section formalize how such measurement-centric mechanisms can be leveraged to enhance robustness against decoherence and operational imperfections, using trapped-ion cluster-state implementations as a concrete and experimentally grounded setting.

5.1. Generation of cluster states with trapped $^{40}Ca^+$ ions

5.1.1. Qubit encoding and initialization

In the trapped-ion experiment, qubits are encoded in the electronic states of a $^{40}Ca^+$ ion:

$$|1\rangle = D_{5/2,\,m=+3/2}, \qquad |0\rangle = S_{1/2,\,m=+1/2}, \tag{18}$$

coupled via a narrow 729 nm optical transition.

A linear chain of n ions confined in a linear Paul trap is initialized into the product state $|1\rangle^{\otimes n}$, through optical pumping. The center-of-mass (COM) and stretch motional modes are cooled to their ground states using resolved sideband cooling, ensuring high-fidelity multi-ion entangling operations.

5.1.2. Interactions used for cluster-state construction

Three interactions are used to generate the desired multi-qubit cluster graph states:

(a) mølmer–sørenson (MS) entangling interaction. This collective entangling gate couples all ions via shared motional modes:

$$M(\chi) = \exp\left(i\chi \sum_{a<b} X_a X_b \right), \tag{19}$$

producing global pairwise entanglement across the ion chain.

(b) single-qubit phase-flip gates. Local Z-rotations are applied to adjust stabilizer phases:

$$G_k(\phi) = \exp\left(i\frac{\phi}{2} Z_k \right). \tag{20}$$

(c) hiding pulses. These pulses temporarily shelve the $|1\rangle$ population in an auxiliary state, effectively removing selected ions from subsequent interactions:

$$F_h = \exp\left(-i\frac{\pi}{4} X_k \right). \tag{21}$$

By appropriately sequencing the $\{M, G, F\}$ interactions, the experiment generates both one-dimensional and two-dimensional cluster states suitable for MBQC.

5.1.3. Resulting 4-qubit linear cluster state

We are showing equivalent quantum circuit for a four-qubit linear cluster. The experimentally generated four-qubit linear cluster state

E_{LC4} is

$$E_{LC4} = \frac{1}{8}\Big(|0000\rangle + i|0011\rangle + |0101\rangle + i|0110\rangle + i|1001\rangle + |1010\rangle + i|1100\rangle + |1111\rangle\Big), \tag{22}$$

which is equivalent to the ideal cluster state up to local single-qubit corrections.

The measured state fidelity is

$$F = 0.841 \pm 0.006. \tag{23}$$

5.2. Universal MBQC gate demonstrations

Cluster states act as a substrate for teleportation-based quantum computation. Logical gates are implemented through single-qubit measurements in rotated bases:

$$B(\alpha) = \{\, |+\alpha\rangle,\ |-\alpha\rangle \,\}. \tag{24}$$

5.2.1. Single-qubit logical gates

Using Euler-angle decompositions, the experiment performs arbitrary single-qubit rotations by:

1. Sequential measurements along the cluster "wire",
2. Classical feedforward of Pauli corrections based on measurement outcomes.

The average experimental fidelity of single-qubit logical gates is

$$F_{1Q} = 0.92 \pm 0.01. \tag{25}$$

5.2.2. Two-qubit controlled-z (CZ) gate

Using the four-qubit linear cluster state LC_4, the experiment implements a teleported CZ gate.

Protocol:

- **Inputs:** qubits 1 and 4 prepared in $|+\rangle|+\rangle$,
- **Measurements:** qubits 1 and 4 are measured in rotated bases $B(\alpha)$ and $B(\beta)$,
- **Outputs:** the logical output state emerges on qubits 2 and 3,

followed by Pauli feedforward determined by the measurement outcomes.

Correction operator:

$$C = (X_2 Z_3)^{s_1} (X_3 Z_2)^{s_4}, \tag{26}$$

where $s_1, s_4 \in \{0, 1\}$ are the binary outcomes of the measurements on qubits 1 and 4.

Measured fidelities:

$$\text{Entangled output:} \quad F = 0.88 \pm 0.02, \tag{27}$$

$$\text{Separable output:} \quad F = 0.83 \pm 0.01. \tag{28}$$

This demonstrates a universal gate set for MBQC implemented on trapped-ion cluster states.

5.3. Cluster-state quantum error correction (QEC)

Using an extended cluster configuration EC_n, the authors implement a phase-flip quantum error-correcting code. For $n = 5$, the encoded cluster state is

$$|EC_5\rangle = |0\rangle_A |+\rangle_{C_1} \cdots |+\rangle_{C_5} |0\rangle_B + |0\rangle_A |+\rangle_{C_1} \cdots |+\rangle_{C_5} |1\rangle_B. \tag{29}$$

The measurement pattern supports:

1. Teleportation of the logical qubit from input qubit A to output qubit B,
2. Syndrome extraction through Pauli-X measurements on qubits $C_1, \ldots, C_5$.

Error-correction rule:

- If more than $(n-1)/2$ measurement results are $|+\rangle$: no correction is applied.
- If more than $(n-1)/2$ results are $|-\rangle$: apply the correction X_B.

Thus the code corrects up to $(n-1)/2$ phase flips, consistent with stabilizer QEC theory.

5.4. Continuous measurement and initial-state estimation via perturbative lindblad dynamics

We now integrate a perturbative method for recovering the initial quantum state under continuous monitoring. The system obeys the Lindblad master equation

$$\dot{\rho}(t) = -i[H_0 + \epsilon V, \rho(t)] + \mathcal{L}(\rho(t)), \tag{30}$$

with

$$\mathcal{L}(\rho) = \frac{1}{2}\sum_{k=1}^{2}\left(L_k \rho L_k^\dagger - L_k^\dagger L_k \rho - \rho L_k^\dagger L_k\right). \tag{31}$$

We expand the solution in powers of the small parameter ϵ:

$$\rho(t) = \rho_0(t) + \epsilon\rho_1(t) + \epsilon^2\rho_2(t) + O(\epsilon^3). \tag{32}$$

5.4.1. Order-by-order perturbative equations

Zeroth order:

$$\dot{\rho}_0 = -i[H_0, \rho_0] + \mathcal{L}(\rho_0), \qquad \rho_0(0) = \rho_{\text{in}}. \tag{33}$$

First order:

$$\dot{\rho}_1 = -i[H_0, \rho_1] + \mathcal{L}(\rho_1) - i[V, \rho_0], \qquad \rho_1(0) = 0. \tag{34}$$

Second order:

$$\dot{\rho}_2 = -i[H_0, \rho_2] + \mathcal{L}(\rho_2) - i[V, \rho_1], \qquad \rho_2(0) = 0. \tag{35}$$

All three orders share the homogeneous propagator generated by the unperturbed Liouvillian:

$$G_0(\cdot) = -i[H_0, (\cdot)] + \mathcal{L}(\cdot), \qquad \Phi_t = e^{tG_0}. \tag{36}$$

5.4.2. Formal solutions (Duhamel integrals)

$$\rho_0(t) = \Phi_t[\rho_{\text{in}}] \tag{37}$$

$$\rho_1(t) = -i\int_0^t \Phi_{t-s}\big([V, \rho_0(s)]\big)\, ds \tag{38}$$

$$\rho_2(t) = (-i)^2 \int_0^t ds\, \Phi_{t-s}\left[V, \int_0^s du\, \Phi_{s-u}([V, \rho_0(u)])\right] \tag{39}$$

These propagator kernels guarantee Hermiticity preservation at every order.

5.5. Observable averages and second-order estimator $P_2(t)$

For any Hermitian observable O,

$$\langle O\rangle(t) = \mathrm{Tr}[O\rho_0(t)] + \epsilon\,\mathrm{Tr}[O\rho_1(t)] + \epsilon^2\,\mathrm{Tr}[O\rho_2(t)]. \tag{40}$$

The second-order estimator $P_2(t)$ is defined through

$$P_2(t) = -i\int_0^t \mathcal{L}(V)\, ds + \int_0^t \mathcal{L}(\rho_0(s))\, ds + \int_0^t \mathcal{L}(V)\rho_1(s)\, ds. \tag{41}$$

Thus,

$$\langle O\rangle^{(2)}(t) = \mathrm{Tr}[O\rho_0(t)] + \epsilon\,\mathrm{Tr}[O\rho_1(t)] + \epsilon^2\,\mathrm{Tr}[OP_2(t)] \tag{42}$$

5.6. Matrix-element representation and linear system

In a basis $\{|\phi_m\rangle\}$, the density matrix components satisfy linear ODEs.
Zeroth order:

$$\dot{\rho}^{(0)}_{mn} = \sum_{pq} A^{(0)}_{mn;pq}\, \rho^{(0)}_{pq}. \tag{43}$$

First order:

$$\dot{\rho}^{(1)}_{mn} = \sum_{pq} A^{(0)}_{mn;pq}\, \rho^{(1)}_{pq} + \sum_{pq} B^{(1)}_{mn;pq}\, \rho^{(0)}_{pq}. \tag{44}$$

Second order:

$$\dot{\rho}^{(2)}_{mn} = \sum_{pq} A^{(0)}_{mn;pq}\, \rho^{(2)}_{pq} + \sum_{pq} B^{(1)}_{mn;pq}\, \rho^{(1)}_{pq} + \sum_{pq} C^{(2)}_{mn;pq}\, \rho^{(0)}_{pq}. \tag{45}$$

The complete perturbative solution is

$$\begin{aligned}\rho(t) = \Phi_t[\rho_{\text{in}}] - i\epsilon \int_0^t \Phi_{t-s}\big([\,V, \Phi_s[\rho_{\text{in}}]\,]\big)\, ds \\ - \epsilon^2 \int_0^t ds\, \Phi_{t-s}\left[V,\ \int_0^s du\, \Phi_{s-u}\big([V, \Phi_u[\rho_{\text{in}}]]\big)\right] + O(\epsilon^3).\end{aligned} \tag{46}$$

For any observable,

$$\langle O\rangle(t) = \mathrm{Tr}[O\rho_0(t)] + \epsilon\, \mathrm{Tr}[O\rho_1(t)] + \epsilon^2\, \mathrm{Tr}[O\rho_2(t)] + O(\epsilon^3) \tag{47}$$

The resulting discrepancy between the theoretical continuous-measurement state estimate and the MBQC cluster-state measurements is finally filled. With this breakthrough in quantum computing, we can finally understand how different quantum computing methods interact with one another. Further study and developments in quantum information processing are also made possible by this. This finding also paves the way for potential improvements to quantum information processing systems' accuracy and efficiency.

6. Discussion and emerging trends

6.1. Architectural trends

Recent efforts in scalable quantum computing increasingly converge toward modular and hybrid architectures, motivated by the control and error-scaling limitations inherent in monolithic systems. At the same time, emerging advances underscore the suitability of MBQC for distributed environments. Van Montfort et al. [58] proposed fault-tolerant MBQC protocols based on diamond-lattice cluster states, which improve upon conventional cubic lattices by supporting more flexible fusion operations, reducing percolation thresholds, and enabling robust topological encoding under realistic noise conditions. Their results show that diamond lattices not only enhance fault tolerance but also naturally accommodate the modular connectivity inherent in distributed architectures. In a complementary direction, Chandra et al. [138] introduced a multiplexed bi-layered architecture in which optically networked trapped-ion modules are entangled via photonic links to form a distributed RHG lattice. This architecture demonstrates how topologically protected MBQC can be realized across physically separated nodes, leveraging modular ion-trap technology while maintaining the error thresholds of large-scale 3D cluster states. Additionally, Omkar et al. [135] presented an all-photonic MBQC architecture based on GHZ-state resources, achieving photon-loss thresholds exceeding 11% under topological error-correction schemes, marking one of the most robust optical implementations reported to date.

Building upon this hardware–software synergy, hybrid CBQC–MBQC co-design frameworks have emerged as a leading architectural trend. Zwerger, Briegel, and Dür [139] first formalized hybrid architectures that integrate deterministic gate execution with measurement-based adaptive logic, providing a theoretical foundation for encoded MBQC. More recent works such as [140], which explore hybrid Pauli based compilation, and Corli [141], which introduces a general measurement-based compiling framework, extend these ideas to practical compilation pipelines capable of translating circuit models into MBQC compatible graph states. Similarly, Cuomo et al. [142] proposed an optimized compiler for distributed quantum computing that dynamically maps circuit segments onto networked resources, exemplifying the emerging co-design philosophy that jointly optimizes algorithmic structure, topology, and fault-tolerant execution. These hybrid approaches underscore a paradigm shift, rather than adhering strictly to circuit or measurement models, future scalable architectures will integrate both paradigms, leveraging the deterministic reliability of gate-based execution and the flexibility, adaptivity, and modularity of measurement-based computation.

6.2. Hardware realizations

The practical realization of measurement-based and modular quantum architectures is being driven by three dominant hardware platforms, photonic systems, trapped-ion modules, and superconducting circuits, each offering distinct operational advantages, with complementary studies addressing physics-driven gate realization and control optimization [143,144]. The comparison among them is summarized in Table 6.

Recent experimental work has made tangible progress toward modular, measurement-driven quantum architectures by delivering scalable resource-state generation, high-fidelity photonic links, and hybrid transduction technologies. In the photonic domain, time-domain multiplexing produced very large continuous-variable cluster states that is a foundational resource for MBQC, as demonstrated by Asavanant et al. [145] using two-dimensional time-multiplexed CV cluster states. Building on such large-scale CV resource states, recent studies have explored coherent computation and algorithmic primitives directly within squeezed-state photonic platforms, highlighting the feasibility of computation and simulation in continuous-variable photonic architectures [146,147]. More recently, deterministic emission of two-dimensional ladder-type cluster states from a superconducting device shows how on-chip sequential emission techniques can synthesize discrete-variable cluster resources suitable for measurement-based protocols [148]. Work on tailored fusion-based photonic architectures and loss-tolerant fusion schedules provides concrete protocols to convert these photonic primitives into fault-tolerant FBQC/MBQC pipelines [113].

Trapped-ion systems have demonstrated increasingly reliable ion–photon interfaces and high-fidelity, time-bin photonic links that are directly usable for distributed MBQC. High-fidelity remote entanglement mediated by time-bin photons was reported recently, achieving heralded Bell-state fidelities compatible with modular, networked operation [149]. Complementary experiments on low-noise quantum frequency conversion convert ion-emitted photons to telecom bands, a necessary step for loss-efficient interconnects in modular systems [150].

For superconducting platforms, coherent microwave-to-optical transduction and device architectures for on-chip cluster synthesis are maturing. Recent theoretical and experimental studies have advanced microwave–optical transduction designs suitable for connecting cryogenic modules to photonic networks [151,152]. Taken together, these peer-reviewed developments provide the essential hardware building blocks, scalable cluster-state sources, low-noise frequency conversion, and transduction interfaces for realizing modular, measurement-based quantum computing across heterogeneous nodes.

6.3. Software and compiler

The software stack for networked, measurement-based quantum architectures is evolving rapidly to handle the adaptive and distributed

Table 6
Characteristics of hardware platforms.

Aspect	Photonic platforms	Trapped-Ion platforms	Superconducting platforms
Qubit Carrier	Photons.	Electronic states of trapped ions.	Microwave photons in transmon or flux qubits.
MBQC Compatibility	Native via cluster or fusion-based schemes.	Deterministic cluster generation via optical interconnects.	Circuit-level cluster states using parametrically driven couplers.
Gate / Readout Speed	Sub-ns operations.	μs-scale gates, fast detection.	10–300 ns gates, fast readout.
Fidelity	∼99% (loss-limited).	>99.9% (deterministic entanglement).	∼99.5% (tunable couplers).
Coherence Time	Limited by optical loss.	ms–s range.	100–400 μs.
Scalability Pathway	Time/spatial multiplexing; silicon photonics.	Modular traps with photonic or microwave links.	2D chip lattices with inter-chip couplers.
Key Challenges	Loss, probabilistic sources, detector inefficiency.	Coupling loss, cryogenic control.	Crosstalk, fabrication yield, cryogenic load.

nature of MBQC. Static circuit compilers are inadequate for coordinating real-time measurement dependencies, classical feed-forward logic, and inter-module latency. Recent efforts focus on adaptive measurement scheduling, where measurement bases dynamically depend on prior outcomes. Oliveira et al. [153] demonstrate temporally flat MBQC scheduling emphasizing architecture-aware constraints, while Zhang et al. [154] introduce OneAdapt, a resource-adaptive compiler optimizing photonic one-way computing by integrating quantum error-correction yields and minimizing fusion-device overheads.

Parallel advances in hybrid CBQC–MBQC compilation enable dynamic algorithm partitioning between circuit-based and measurement-based segments. Sunami and Fukushima [155] proposed Graphix, which optimizes MBQC graph structures via local-Clifford transformations to reduce resource costs and enable modular execution. At the system level, network-aware runtimes such as Qiskit Runtime and t|ket> are starting to incorporate primitives for classical-quantum feedback and adaptive measurement management, connecting compiler logic with distributed control frameworks [45].

6.4. Industry and ecosystem perspective

Industrial activity in quantum computing increasingly reflects a strategic shift toward scalable, modular, and fault-tolerant architectures. Major companies are advancing multiQPU platforms, quantum networking technologies, and system architectures aligned with emerging quantum-enabled communication infrastructures, alongside high-performance classical control systems that enable distributed execution across interconnected quantum modules [156]. IBM's Quantum System Two exemplifies this direction, introducing a multi-chip cryogenic architecture engineered for modular expansion and real-time hybrid control [157]. Similar progress is evident in trapped-ion platforms, including IonQ's demonstration of remote ion-ion entanglement between spatially separated traps and Quantinuum's continued development of extensible architectures emphasizing cross-module connectivity [158,159].

Parallel developments across the broader ecosystem reinforce this modular trajectory. Rigetti's multi-chip superconducting processor, Pasqal's scalable neutral-atom roadmap, and QpiAI's deployment of a 25-qubit superconducting stack under India's National Quantum Mission each demonstrate growing industrial commitment to modular system engineering [160–162]. Networking-focused efforts, such as Nu Quantum's quantum networking unit for high-rate entanglement distribution, further highlight the emergence of infrastructure oriented toward datacenter-scale quantum interconnects [163]. Among major companies, PsiQuantum remains distinctive in explicitly pursuing a photonic, measurement-driven, fusion-based architecture, representing the only large-scale industrial program directly aligned with MBQC/FBQC principles [132,164].

6.5. Synthesis and outlook

Recent advances across architectures, hardware platforms, software infrastructures, and industrial initiatives collectively signal a fundamental shift in how scalable and fault tolerant quantum computing systems are being designed. Rather than extending monolithic processors indefinitely, the field is converging toward modular, networked, and heterogeneous architectures that distribute complexity across interconnected quantum nodes. Within this evolving landscape, the measurement-based model emerges not merely as an alternative computational paradigm, but as a system-level abstraction that aligns naturally with the operational constraints and opportunities of fault-tolerant and distributed quantum computing.

From a systems perspective, MBQC enables a structural separation between entanglement distribution and logical processing, allowing resource-intensive operations to be decoupled from online computation and coordinated across modular nodes. This abstraction facilitates hardware heterogeneity, reduces sensitivity to interconnect variability, and supports topologically protected fault-tolerant execution using distributed graph and cluster states. When integrated with recent advances in adaptive compilation, latency-aware scheduling, and hybrid CBQC–MBQC execution models, MBQC provides a flexible framework for orchestrating computation in networked quantum systems.

At the same time, the literature reveals several challenges that cut across platforms and architectural choices. The scalable generation of high-fidelity resource states remains constrained by loss, decoherence, and imperfect inter-module connectivity, particularly in photonic and hybrid settings. Moreover, the adaptive feed-forward structure intrinsic to MBQC places stringent demands on classical control, synchronization, and real-time error tracking, especially as systems scale geographically and technologically. Addressing these challenges requires system-level solutions that jointly consider hardware capabilities, control latency, and software abstractions.

Looking forward, the transition from experimental prototypes to deployable distributed quantum systems will rely on sustained co-design across hardware, control, and software layers. Progress in modular node engineering, photonic networking, and transduction technologies must be complemented by compiler–runtime stacks capable of dynamically adapting computation to noise, latency, and resource availability. Beyond computation alone, MBQC's inherent support for measurement-driven and delegated protocols also positions it as a promising foundation for secure and cloud-based quantum services. Taken together, these considerations suggest that measurement-based approaches will play a central role in shaping scalable and fault-tolerant quantum architectures as the field matures.

Declaration of generative AI and AI-assisted Technologies in the writing process

During the preparation of this work, the authors used generative AI tools solely to improve language clarity and readability. After using these tools, the authors reviewed, edited, and validated all content, and they take full responsibility for the final version of this manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors would like to express their gratitude to QRACE and Egreen Quanta for facilitating this lab for work. We are truly thankful for their collaboration and assistance throughout the process.

Data availability

No new data were created or analyzed in this study. Data sharing is therefore not applicable to this article.

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