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# Noise-Aware Detectable Byzantine Agreement for Consensus-based Distributed Quantum Computing

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***Abstract*—In distributed quantum computing (DQC), achieving consensus with adversarial elements presents a critical challenge. This paper proposes an innovative framework that enhances the Quantum Byzantine Agreement (QBA) protocol by integrating practical quantum error mitigation techniques, specifically Quantum Readout Error Mitigation (QREM) and Dynamical Decoupling (DD). Utilizing Noisy Intermediate-Scale Quantum (NISQ) devices, our approach aims to improve operational reliability significantly. Our results demonstrate that QREM and DD effectively mitigate common quantum channel errors through rigorous experimentation on both simulated environments and IBM's quantum hardware. The proposed protocol also introduces a verification mechanism inspired by Quantum Key Distribution (QKD) systems, ensuring the secure transmission of commands encoded in quantum states. In cases of discrepancies, lieutenants engage in systematically designed interactions to achieve consensus, influenced by the Commander's strategic decisions and the network's size. Our empirical analysis highlights the protocol's enhanced resilience and efficiency under various conditions, while also addressing challenges related to scalability as the network size increases.**

***Index Terms*—Distributed Quantum Computing, Quantum Internet, Quantum Error Mitigation, Dynamic Decoupling, Noise Resilience**

## I. INTRODUCTION

Distributed quantum computing faces critical challenges in achieving consensus within decentralized networks, particularly when addressing Byzantine Agreement (BA) problems where classical solutions falter with over one-third faulty processes. The Detectable Byzantine Agreement (DBA) exemplifies quantum computing's potential to resolve classically intractable consensus issues, leveraging quantum protocols to overcome adversarial limitations [1]–[5]. However, Noisy Intermediate-Scale Quantum (NISQ) devices introduce channel errors and decoherence, necessitating noise-aware protocols. We propose a robust quantum distributed computing framework integrating advanced quantum error mitigation (QEM) techniques: Dynamical Decoupling (DD) to suppress idle qubit decoherence [6] and Twirled Readout Error Extinction (T-REx) for measurement noise correction [7]. These methods, validated through IBM's Qiskit Runtime, enhance stability in adversarial environments, addressing the fragility of quantum states while preserving theoretical guarantees [8]–[10].

The evolution of quantum networks and the quantum internet amplifies the need for scalable, secure consensus mechanisms [11], [12]. Quantum internet architectures merge quantum and classical communication to enable teleportation and entanglement, forming the backbone for distributed quantum computing [13]–[15]. Concurrently, decentralized trust management systems, such as blockchain, demand quantum-enhanced consensus protocols to counter classical vulnerabilities. By utilizing Greenberger-Horne-Zeilinger (GHZ) states, our framework extends DBA to multi-party quantum networked systems, ensuring secure data consensus in zero-trust environments [16], [17]. This synergy between quantum computing and blockchain establishes a resilient, decentralized paradigm for future networks.

Figure 1 illustrates our distributed architecture, which integrates classical task scheduling with quantum processing

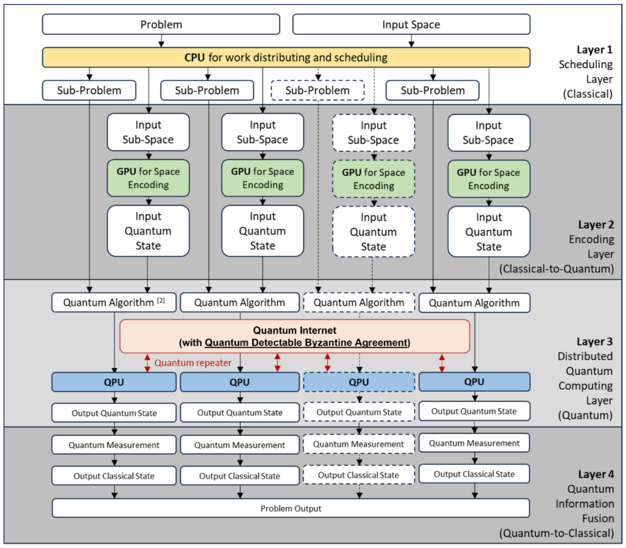

Figure 1. Schematic representation of a distributed quantum computing architecture, illustrating the integration of classical scheduling with quantum processing through various layers, encompassing space encoding, quantum algorithms execution, quantum internet communication, and the transition from quantum to classical information.

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across layered modules [18]–[20]. Quantum states generated at the encoding layer are processed via distributed Quantum Processing Units (QPUs), interconnected by a quantum internet backbone that ensures coherent communication [21], [22]. This design enables scalable parallelism, which is critical for NISQ-era algorithms such as privacy-preserving Quantum Federated Learning (QFL) [23]–[25], distributed quantum kernel learning [26], and distributed variational quantum algorithms [27]–[30]. Furthermore, the architecture inherently supports privacy preservation by ensuring that data exchanged among distributed QPUs remains secure and anonymized during processing. In addition, by aggregating classical outputs from distributed QPUs, the system optimizes combinatorial solvers (eg. QAOA) [31]–[33] and aligns with quantum-HPC initiatives [14], [34]. This integration bridges quantum and classical resources, advancing both computational power and secure, privacy-preserving data ecosystems.

In this paper, we introduce a noise-aware, adaptive quantum error mitigation scheme for distributed quantum computing targeting NISQ devices. Our empirical analysis highlights the protocol's enhanced resilience and efficiency under various conditions, while also addressing challenges related to scalability as the network size increases.

## II. PROTOCOL STRUCTURE

In distributed quantum computing networks, achieving consensus across QPUs distributed across various nodes is crucial, especially when addressing the challenges presented by the Quantum Byzantine Agreement (QBA) protocols. The proposed noise-aware quantum DBA protocol, illustrated in Fig. 2(a) and (b), provides a robust method for ensuring the integrity and reliability of the consensus process, even in the presence of potentially dishonest participants. This section outlines the core steps of the quantum DBA protocol:

1) **Distribution of Quantum Resources:** The protocol begins with the distribution of quantum resources, such as entangled qubits, among all participating nodes, referred to as "generals" in the Byzantine Agreement context [35]. This distribution is facilitated through secure quantum channels, establishing a shared quantum state among participants. This shared state is essential as it underpins the subsequent quantum communication and consensus-building processes.
2) **Verification of Entanglement:** After the quantum resources have been distributed, participants verify the entanglement correlations to confirm the expected properties of the shared quantum states. This step may involve procedures such as Bell tests [36] or quantum state tomography techniques, like the GHZ state [16]. These methods ensure that the quantum resources remain in a secure and reliable state, acting as a safeguard against potential eavesdropping or tampering.
3) **Order Issuance:** The commander, utilizing the established quantum channel, securely transmits orders to the lieutenants. Thanks to the properties of quantum entanglement, these orders cannot be intercepted or altered without detection. Each lieutenant receives and stores the orders for the upcoming consensus process.
4) **Consensus Building:** Upon receiving the orders, the lieutenants engage in a consensus-building phase, leveraging their entangled states for secure communication regarding the commander's directives. This phase may include quantum operations designed to identify and isolate any deceptive nodes [5]. Techniques such as quantum voting [37], superdense coding [38], and entanglement-swapping [39] are employed to ensure the authenticity of the orders. If consensus is reached, the lieutenants proceed accordingly; otherwise, conflict resolution protocols are invoked. Nodes identified as persistently dishonest or non-cooperative are excluded from further participation to maintain the integrity of the process.

The quantum DBA protocol harnesses the principles of quantum mechanics to ensure secure, efficient, and reliable consensus in distributed networks, even in environments where

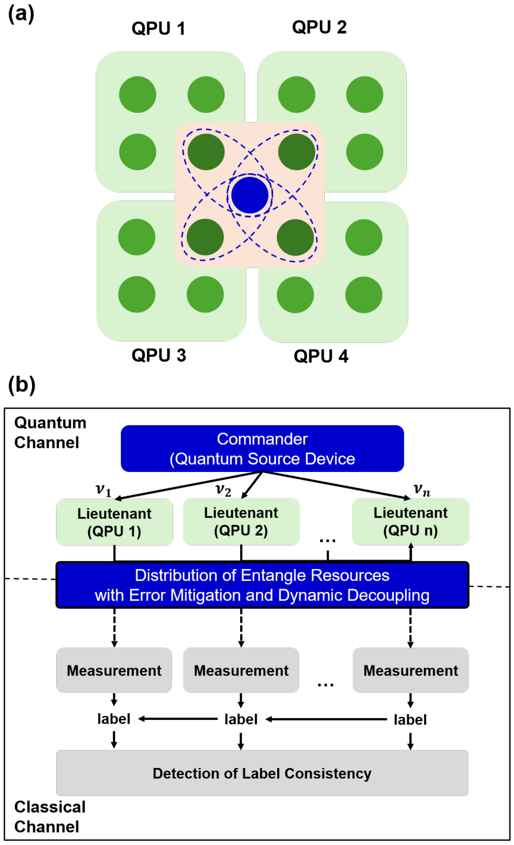

Figure 2. (a) Conceptual diagram for DQC using the proposed protocol. The diagram illustrates the interaction among multiple QPUs, with entanglement resources being shared across the network to achieve consensus. (b) Flowchart depicting the quantum DBA protocol with integrated error-mitigation and dynamic decoupling strategies. The structure emphasizes the roles of the Commander (quantum source device) and Lieutenants (QPUs), followed by processes for entanglement distribution, error correction, quantum measurements, and the final step of label consistency detection.

traditional methods might be vulnerable to security threats. The integration of QEM techniques is vital in enhancing the fidelity of quantum states, ensuring operational integrity despite the inherent error susceptibility in quantum computing. Additionally, strategies to counteract decoherence, such as DD, are employed to preserve the coherence of quantum states, further strengthening the reliability and accuracy of the consensus process. Together, these advanced techniques fortify the protocol, making it a robust solution in the rapidly evolving landscape of quantum communications.

### *A. Distribute Entanglement*

Let $n$ be the total number of generals ($n > 2$), with the Commander holding two qubits and each Lieutenant holding one. The distributed entangled state is defined as:

$$|\Psi_n\rangle \equiv \frac{1}{\sqrt{3}}\Bigg[ |00\rangle\,|1\rangle^{\otimes(n-1)} + |11\rangle\,|0\rangle^{\otimes(n-1)} + \frac{1}{\sqrt{2(n-1)}}\Bigg( |01\rangle \sum_{i=0}^{n-2} |0\rangle^{\otimes(n-2-i)}\,|1\rangle\,|0\rangle^{\otimes i} + |10\rangle \sum_{i=0}^{n-2} |1\rangle^{\otimes(n-2-i)}\,|0\rangle\,|1\rangle^{\otimes i} \Bigg)\Bigg]. \tag{1}$$

The state's symmetry ensures uniform measurement correlations:

- If the Commander measures $|00\rangle$ or $|11\rangle$, all Lieutenants collapse to $|1\rangle$ or $|0\rangle$, respectively (deterministic consensus).
- If the Commander measures $|01\rangle$ or $|10\rangle$, exactly one Lieutenant measures $|1\rangle$ (probabilistic consensus).

### *B. Verify Entanglement*

After distributing $k$ copies of $|\Psi_n\rangle$, a subset $S \subseteq \{1, \ldots, k\}$ is selected for verification via a pre-shared classical randomness source (e.g., agreed via QKD [36]), resolving the reviewer's ambiguity about index selection. All generals measure qubits in $S$, exchanging outcomes to compute correlation fidelity:

$$\mathcal{F} = \frac{1}{|S|} \sum_{i \in S} \delta\Big(\text{Commander}_i, \text{Lieutenants}_i\Big), \tag{2}$$

where $\delta$ is 1 if outcomes match the expected correlations in $|\Psi_n\rangle$, else 0. If $\mathcal{F} < 1 - \epsilon$ (noise threshold $\epsilon$), the batch is discarded.

### *C. Distribute Order*

The Commander encodes orders as classical bitstrings: $00$ = Retreat, $11$ = Attack. For each remaining copy $j \in \{1, \ldots, k\} \setminus S$:

- If the Commander measures $|00\rangle$ or $|11\rangle$, all Lieutenants' qubits collapse uniformly (no index grouping needed).
- If the Commander measures $|01\rangle$ or $|10\rangle$, they group indices $j$ by the Lieutenant's unique $|1\rangle$ outcome (e.g., index $j$ corresponds to Lieutenant $\ell$ if

$$|\psi_j\rangle = |01\rangle\,|0\rangle^{\otimes(\ell-1)}\,|1\rangle\,|0\rangle^{\otimes(n-1-\ell)}.$$

The order and grouped indices are broadcast classically. Lieutenants verify consistency by cross-referencing their own measurement outcomes with the Commander's claimed groupings.

### *D. Noise-Aware Protocol for Quantum DBA*

The adaptive use of QEM (Algorithm 1) is justified by the overhead trade-off: DD and T-REx incur $O(n^2)$ runtime

**Algorithm 1** Protocol Execution for Noise-Aware Detectable Byzantine Agreement

```
Require: Number of generals $N_{\text{gen}}$, Number of traitors $N_{\text{traitors}}$, Number of shots shots, Noise level noise, Number of batches num_batches, Verbose flag verbose
Ensure: Consensus results consensus_results
Procedure run_qdpa($N_{\text{gen}}, N_{\text{traitors}}$, shots, noise, num_batches, verbose):
Initialize q_device ← Quantum_Source_Device($N_{\text{gen}}$, noise)
Generate entangled states using q_device.run_circuit(shots × num_batches)
Reshape q_device.measurements into batched_measurements of shape (num_batches, shots, $N_{\text{gen}}$)
Initialize consensus_results ← [ ]
for each batch in batched_measurements do
    Initialize qbs ← Quantum_Byzantine_Scheme($N_{\text{gen}}$, shots, noise, batch, verbose)
    Verify entanglement with qbs.verify_entanglement()
    Randomly assign traitor status using qbs.flip_allegiance(random_selection($N_{\text{gen}}$, $N_{\text{traitors}}$))
    Distribute orders with qbs.send_orders()
    Execute agreement process with qbs.realize_agreement()
    Check for detectable broadcast (consensus achievement) with qbs.detectable_broadcast()
    Append consensus_results with consensus
end for
Calculate success_rate ← calculate_success_rate(consensus_results)
if success_rate < SUCCESS_THRESHOLD then
    Enable error mitigation with enable_error_mitigation()
    Enable dynamic decoupling with enable_dynamic_decoupling()
    Rerun protocol with enhanced techniques: q_device.run_circuit(shots × num_batches)
    Reinitialize consensus_results ← [ ]
    for each batch in batched_measurements do
        Reinitialize qbs and repeat the protocol steps
    end for
end if
return consensus_results
```

Table I
COMPARISON WITH OTHER QUANTUM BYZANTINE PROTOCOLS.

| Protocol | Comm. Complexity | Entanglement Resources | Purpose | Fault-Tolerant | Noise-Aware? |
|---|---|---|---|---|---|
| **Proposed** | $O(n^2)$ | $n$-particles entangled qubits | n-party DBA | $t < n/2$ | ✓ |
| [40] | $O\left(p(n-t)^2\right)$ | 3-particle entangled qutrits | 3-party DBA | $t < n/2$ | ✗ |
| [36] | $O(kn^4 \log n)$ | Bell state | n-party DBA | $t < n-1$ | ✗ |
| [5] | $O\left(p(n-t)^2\right)$ | 4-particles entangled qutrits | 3-party DBA | $t < n/2$ | ✗ |
| [41] | $O(n^2 t)$ | 4-particles entangled qutrits | n-party DBA | $t < n/2$ | ✗ |
| [35] | $O(t+1)$ | $(q-1)$-particles entangled qubits | n-party DBA | $t < n-1$ | ✗ |
| [16] | $O\left(n^2\right)$ | GHZ state | $n$-party DBA | $t < n-1$ | ✗ |

scaling versus $O(n^3)$ for full error correction. Unlike prior protocols (Table I), our QEM is protocol-aware:

- DD is applied only to idle qubits during multi-round communication, suppressing decoherence without added gates during active phases.
- T-REx mitigates readout errors asymmetrically, preserving the $|0\rangle / |1\rangle$ bias critical for GHZ-state consensus (Fig. 3).

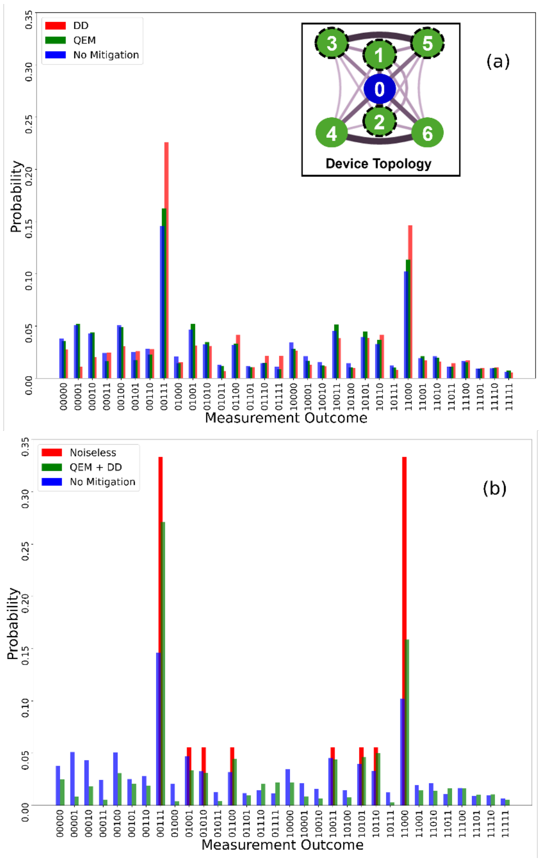

Figure 3. $(a)$ And $(b)$, respectively depict the measurement outcomes of the initial state with and without QEM (T-REx) and DD. The depicted probability mass functions are the averages of 100 iterations of measuring the prepared state with $n = 4$, on IBM's Nairobi quantum computer available via Qiskit Runtime with each iteration containing 8192 shots.

Classical protocols cannot leverage this asymmetry, as their consensus hinges on bit-flip symmetry.

## III. RESULTS

The proposed protocol was tested under varying conditions to determine the effective scaling of the scheme and assess the impacts of noise and the effectiveness of the quantum error mitigation techniques examined. This exploration was limited to a maximum network size of $n = 6$ due to the maximum number of qubits available on chosen hardware.

In Fig.4 as expected, the unmitigated case exhibits the lowest probability of success ($p_0 = 0.6368$), while the addition of QEM alone is a slight improvement ($p_1 = 0.6611$). The presence of DD drastically improves the success of the

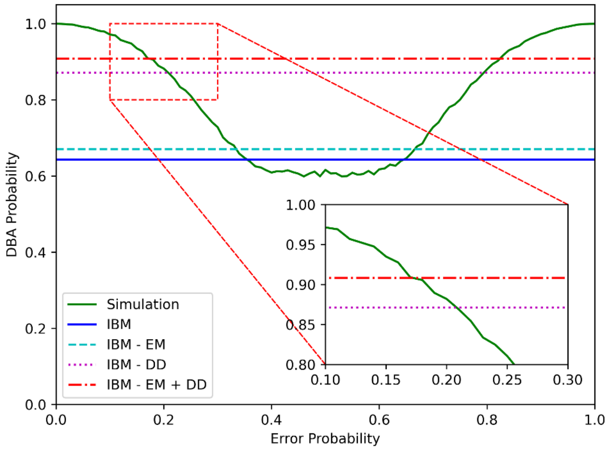

Figure 4. The probability of achieving detectable broadcast in the presence of noise, simulated as bit-flip error compared to using IBM Nairobi with number of indices exchanged (shots) equal to 1000 in the case with the total number of generals $n = 5$ with a single, randomly selected traitor. The noise level represents the probability for any qubit value to flip upon measurement and ranges from 0 to 1 in 100 increments with 10000 iterations being performed at each value. As this scheme depends on the correlations between qubits, the probability of success is necessarily symmetric under reflection about the line where the noise level is 0.5. This represents the point of no correlation, or maximum scrambling, as the noise level increases beyond this anti-correlation occurs which can also be used as an entanglement resource in an identical fashion. Under these parameters, the use of QEM and DD is equivalent to a noise level of 0.175, an improvement over the use of DD alone (0.207), both of which are a dramatic improvement compared to the unmitigated results (0.338).

scheme ($p_2 = 0.8689$) even without the addition of QEM. Interestingly, there is an apparent synergistic effect where the combined QEM and DD success ($p_3 = 0.9093$) shows a 1.663 times greater impact from the QEM than without DD. Even with a noise level of 0.5 the probability of achieving detectable broadcast remains over 0.5 for this scenario. This is expected as the traitor is chosen at random, as well as the order issued by the commander.

In Fig.5 the impact of network size and number of traitors on the success of the protocol is explored. As expected, the addition of traitors reduces the probability of success up until approximately half of the lieutenants are traitors, from which point further addition of traitors reduces the number of loyal lieutenants needing to find consensus. The impact of network size also demonstrates the expected results of reduced success with increasing $n$. The number of shots used in Fig.5 ($10,000$) is sufficient to achieve perfect success $P(DBA) = 1$ up to $n = 5$ for the QEM and DD case. The image of QEM and DD is pronounced in adding robustness to this protocol for all cases explored here.

The scaling behaviour is explored in Fig.6 with respect to the number of indices distributed (shots). This, along with network size affects the protocol computation time. The exponentially increasing number of shots required to achieve near-perfect success, with increasing network size, limits the scalability of this protocol as it operates currently. However, the impact of QEM and DD does dramatically decrease the number of shots needed. Further research with larger systems and higher fidelity hardware will yield more conclusive evidence of the scalability of this protocol.

## IV. DISCUSSION

Our results demonstrate that integrating QEM with distributed consensus protocols overcomes fundamental limitations of classical Byzantine Agreement in adversarial quantum networks. By exploiting the verifiable nonlocal correlations of GHZ states, our protocol ensures Byzantine fault tolerance even under NISQ-era noise, with Dynamical Decoupling and T-REx suppressing decoherence and readout errors to experimentally achievable thresholds. This framework bridges quantum networking and distributed computing, enabling secure multi-party quantum processes—such as federated learning and decentralized blockchain consensus—while maintaining compatibility with hybrid quantum-classical architectures. The scalability of our approach, validated through IBM's quantum infrastructure, underscores its viability as a foundation for large-scale quantum internet applications, where coherent resource distribution and fault-tolerant entanglement sharing are critical. These advances establish a practical pathway toward robust, quantum-enhanced networks that transcend classical security and scalability barriers. Future research will focus on testing this protocol on more extensive quantum hardware and exploring additional error suppression techniques to further enhance its scalability and performance.

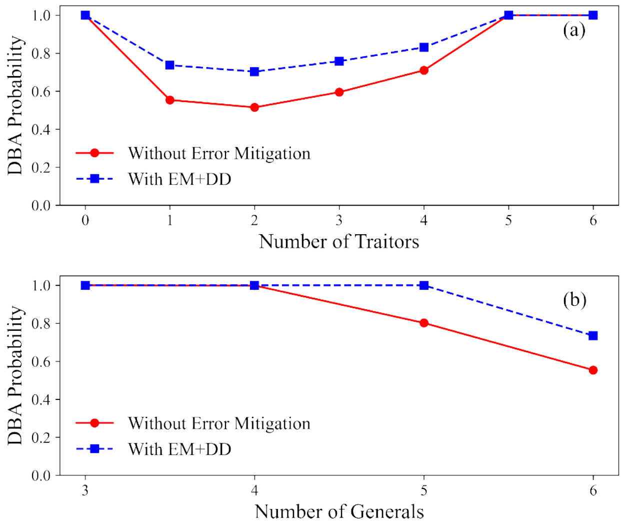

Figure 5. (a) Depicts the probability of achieving detectable broadcast with and without QEM and DD with a fixed network size $n = 6$, and varying numbers of traitors present, while (b) depicts the probability of achieving detectable broadcast with and without QEM and DD in the presence of a single traitor with varying network size. 1000 iterations were performed for each data point, with a number of shots equal to $10,000$. The trivial cases in (a) with a number of traitors $m \in \{0, 5, 6\}$ are demonstrated clearly. In both (a) and (b) the significant performance improvement with the utilization of QEM and DD is visible over the unmitigated case with greater success probability in every non-trivial case.

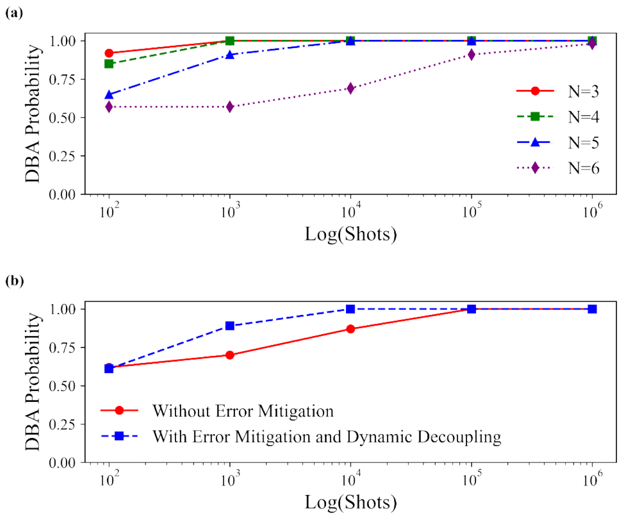

Figure 6. (a) Depicts the probability of achieving detectable broadcast with QEM and DD for a range of different network sizes with increasing number of shots from 100 to $10^6$. As the network size increases, the number of shots needed to achieve near-perfect broadcast, $P(DBA) \approx 1$, increases exponentially. Similarly, (b) depicts the probability of achieving detectable broadcast with and without QEM and DD with a network size $n = 5$. The rate of convergence to near-perfect broadcast is significantly greater with QEM and DD when compared to the unmitigated case. For both figures, 100 iterations were performed at each data point.

## V. Acknowledgments

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