Enhancing Quantum State Transmission Fidelity through Quantum Orthogonal Frequency Division Multiple Access

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Abstract—**In this paper, we propose quantum orthogonal frequency division multiple access (Q-OFDMA), a novel quantum communication scheme designed to overcome the fidelity limitations imposed by noise in multi-user quantum networks. Inspired by its classical counterpart, Q-OFDMA employs the quantum Fourier transform (QFT) and its inverse (IQFT) to encode and decode information across quantum channels. We evaluate our model under both a depolarization channel and a generalized noise model that interpolates between depolarizing and phase-damping noises. The simulation results conducted on Qiskit platform demonstrate that Q-OFDMA outperforms the reference model, achieving superior average fidelity across varying qubit counts and noise levels.**

Index Terms—**Quantum Communication, State Fidelity, OFDMA, Quantum Fourier Transform, Quantum Channel.**

I. INTRODUCTION

QUANTUM communication promises revolutionary advancements in secure information transfers, distributed computing, and quantum networking. The fundamental unit of information in quantum communication is the quantum bit (qubit). Unlike classical bits, which are constrained to be either 0 or 1, qubits can be in coherent superpositions of these states [1]–[3]. Quantum communication is rooted in the fundamental principles of quantum mechanics, most notably entanglement [4]. This phenomenon allows for the instantaneous correlation of quantum states regardless of distances, forming the basis for communication protocols that can achieve unprecedented levels of security [5], [6].

Qubit-based communication technologies have attracted a great deal of interest in view of their ability to offer dramatic performance gains over classical communication schemes [7]. One striking potential of quantum computers is that they can generate algorithms that are exponentially faster for certain problems in computation, optimization, and search [8].In the networking side, a quantum internet is expected to provide communications that are fundamentally secure and more robust than current classical infrastructure [9].

Although quantum communication holds tremendous promise and potential, it has challenges, especially as related to managing error and noise. These errors are a significant obstacle to the realization of scalable quantum devices. Errors accumulate and are significantly detrimental to performance in complex quantum networks constructed by the interconnection of many components [10], [11]. These problems are exacerbated in a quantum multiple-access scenario, where multiple users share a quantum channel simultaneously. Noise in quantum communication systems is commonly due to gate imperfections and different channel noises [12]. The latter are fundamentally due to the inherent interactions between the quantum system and its environment. This procedure severely undermines the integrity and fidelity of quantum state transmission.

The general model of quantum communication is illustrated in Figure 1. The encoder prepares the quantum state in some encoding way according to the probability distribution of the source message. The input to a quantum channel is a quantum state, encoding information into a physical property. This quantum state travels through a quantum communication channel. To retrieve information, the quantum state must be measured at the receiver's end. The measurement outcome, which may be altered, depends on the quantum channel's transformation, which can be either fully probabilistic or deterministic. A quantum channel modifies information encoded in quantum states, such as the spin state of a particle, the ground and excited states of an atom, or other physical properties [13]. There are several important challenges in designing scalable quantum multiple-access systems. One of the main challenges is that quantum states from multiple users must be transmitted simultaneously, yet remain intact [14]. Similarly, quantum channels are also subject to inherent noise sources. In practical quantum state transmission, the ideal quantum communication channel will always stumble due to its environmental noise. Such interaction changes the transmission fidelity from the idealized to the practical.

There is a definition of fidelity, which provides a mathematical formality of how similar two quantum states are. This measure is actually useful in many experimental situations. Its main application is to verify quantum state preparation, which is always prone to noise and imperfections in the process. Here, fidelity quantifies how close the experimentally realized state is to the desired target state [15], [16]. It is a central issue in many fields related to quantum communications or quantum computing, in which quantum states need to be generated and transmitted with exact fidelity but are inevitably subject to decoherence and error.

The quantum Fourier transform and its inverse are the main parts that power our model as QFT and IQFT, respectively.

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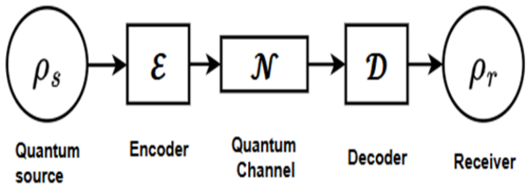

Fig. 1. Basic model of quantum communication.

QFT is an important quantum computing building block, and it is a key subroutine in well-known quantum algorithms, such as Shor's and phase estimation [17]–[20]. A unitary operation that is exponentially faster than its classical implementation, the Fast Fourier Transform (FFT) [21], [22]. It's involved in the encoding of our quantum states. The IQFT, on the other hand, is its mathematical opposite. We use it for decoding. It carries the data back from the frequency domain so we can read it properly. These two transforms are what make our Q-OFDMA functional together; they ensure that we can process and retrieve our data in an efficient manner. This work introduces a new quantum multiple-access method, which we term Quantum-Orthogonal Frequency Division Multiple Access (Q-OFDMA). This approach is motivated by the classical Orthogonal Frequency Division Multiple Access (OFDMA) widely used in LTE and 5G. Classical OFDMA uses approaches such as the Fast Fourier Transform (FFT) to apply an efficient transformation between the time and frequency domains, where, in turn, our Q-OFDMA system uses its theoretical quantum counterpart, the Quantum Fourier Transform (QFT). In our system, the QFT occupies a central role similar to that of the FFT in the standard classical OFDMA, enabling the unique advantages of our quantum-based model.

Our proposed model is a quantum communication scheme from the generation of quantum states to sending them over a quantum channel. While our model applies a centralized QFT operation acting on jointly prepared user qubits, such a model aligns well with centralized quantum repeater nodes or trusted node configurations commonly envisioned in the first-generation quantum internet. These centralized setups can support co-located quantum registers and enable multi-user access via global unitary transformations. Additionally, Q-OFDMA could complement hybrid classical quantum network control planes, serving as a quantum-layer multiplexing technique beneath classical routing. The fidelity of the transmitted quantum state is a key figure of performance; it is involved since this measurement provides the verification and the characterization of the output state of quantum communication. Its measurement is extensively used in quantum data processing, quantum engineering, and quantum machine learning.To evaluate our system's performance, we used two distinct quantum channel models to simulate noise. The first is a standard depolarization channel, which serves as a benchmark for uniform noise. We also considered a second, more complex scenario using a generalized noise model that interpolates between depolarizing and phase-damping noise [23]. This latter scenario was chosen to reflect the inherent uncertainty in noise characterization and allows for a tunable bias toward specific error types, providing a more realistic test of our system's robustness.

The rest of the paper is organized as follows: Section II reviews related work on quantum multiple-access schemes and fidelity analysis, establishing the context for our contribution. In Section III, we present the system model, which includes a description of Q-OFDMA and introduces the two quantum noise channels used for assessment. Section IV presents the mathematical framework for system fidelity under these noise models. To validate the performance of the Q-OFDMA model, the simulation results are introduced in Section V. Finally, Section VI concludes the paper by summarizing the findings and suggesting directions for future work.

II. RELATED WORK

Building upon the foundational context outlined in the introduction, the following review synthesizes the most pertinent related work that contextualizes and motivates the present study. In wireless communication systems to provide several multiple access techniques for efficient usage of the radio spectrum [24]–[26]. These include Time Division Multiple Access (TDMA), Orthogonal Frequency Division Multiple Access (OFDMA), Code Division Multiple Access (CDMA), and Non-Orthogonal Multiple Access (NOMA) [27]. Different strategies that offer unique ways for sharing the scarce spectral resource among multiple users. TDMA allocates available time slots to different users so that collisions are avoided and access to the channel is sequential and organized. OFDMA achieves the diversity gain for multipath fading, and robust to co-channel interference by using differently allocated orthogonal subcarriers. CDMA, on the other hand, allows users to transmit at the same time over the entire spectral bandwidth by using user-specific spreading codes that spread signals in the code domain. The NOMA, as one of the recent techniques, can partially overlap some resources between users; following dividing power multiplexing and intelligent signal processing, it can decode superimposed signals, such as successive interference cancellation (SIC) [28], [29]. The main advantages of these multiple access techniques are efficient interference rejection, better spectrum utilization, and support for high Quality of Service (QoS). By allowing improved exploitation and sharing of the wireless channel, such techniques significantly increase the performance, reliability, and scalability of current communication systems.

The challenge of scalable, trust-free multi-user was addressed by [30], which provided an analysis of time and code division multiple access (TDMA/CDMA) protocols within a passive star network topology. This work is distinguished by its systematic comparison of these multiple access techniques specifically for the demanding low-photon-number regime of quantum key distribution (QKD) [31].In this context, authors in [32] propose a quantum code division multiple access (QCDMA) network architecture that leverages direct sequence spread spectrum (DSSS) techniques at the single-photon level. Their work is distinguished by its use of practical, commercially available optical components to construct an add-drop multiplexer capable of combining multiple single-photon channels into a single optical fiber. while the work in [33] introduces a QCDMA communication system. Their model uses spectral phase encoding to apply pseudorandom barcodes to quantum light pulses.

In the pursuit of enhancing the scalability and key rates of QKD networks, orthogonal frequency-division multiplexing (OFDM) has emerged as a promising spectrally efficient multiplexing technique. Work in [34] demonstrated the feasibility of OFDM for frequency-coded QKD, showing that multiplexing multiple subcarriers could achieve a practical raw key rate across long-distance links, with orthogonal subcarriers and guard bands reducing noise and quantum bit error rate (QBER). Authors in [35] proposed two all-optical OFDM-QKD schemes for trusted-node quantum networks. Their work identified a key limitation of passive OFDM decoders offer no secret key rate gain due to loss. They suggested an active decoder with an optical switch. This design can linearly increase the key rate with subcarriers. Previous studies have explored quantum OFDM-like or frequency-multiplexed communication techniques; however, the proposed Q-OFDMA framework offers a fundamentally different operational and architectural perspective. Existing approaches, such as those in [19] and [20], primarily emphasize frequency-domain multiplexing-based transmission for individuals. In contrast, Q-OFDMA introduces a global QFT-based encoding that jointly processes all user qubits within the quantum register, enabling orthogonal multi-user access through a centralized multiplexing operation. This joint encoding approach distinguishes Q-OFDMA from earlier schemes by emphasizing scalable multi-user access under noisy conditions and by systematically evaluating performance using fidelity-based metrics rather than solely focusing on bit error rates.

Research on quantum state fidelity has been extensively analyzed under various noisy conditions. Authors in [36] highlight that when the entangled resource is subject to correlated noise, the performance degrades, although they derive analytical expressions showing a threshold memory coefficient beyond which teleportation remains viable. In another detailed analysis, authors in [37] demonstrate that the achievable fidelity and the range of teleportable states depend critically on both the type of noise and its point of introduction within the teleportation protocol.

While previous studies have demonstrated the benefits of quantum techniques in communication contexts, they often overlook scalable integration within orthogonal multi-user frameworks. To address this, the present paper proposes Q-OFDMA model using quantum encoding and QFT techniques. The study examines how system fidelity changes with different user counts and depolarizing noise. It focuses on channels with varying depolarization levels. The goal is to improve multi-user communication and support future progress in quantum communication systems.

III. SYSTEM DESCRIPTION

This section describes in detail the Q-OFDMA model and its elements. We express the Q-OFDMA and a conventional reference model that is used as a benchmark of performance. The quantum channel is a basic barrier to information transmission based on our model. It is a source of error that degrades the fidelity of the transmitted state. Here, we introduce the common noise model illustrated by the depolarization channel model to serve as a baseline for unitary noise. For a more realistic analysis, we also made use of a generalized noise model that combines the effect of phase flip and depolarizing noises.

A. Q-OFDMA scheme

The Q-OFDMA model extends conventional OFDMA into the quantum domain by employing the quantum Fourier transform (QFT) and its inverse (IQFT) [38]. OFDMA functions as an essential multi-user communication technology for current broadband wireless networks, based on which computationally-efficient orthogonal subcarrier assignments are implemented. The main principle behind it is to divide the wideband radio spectrum into a number of narrowband sub-carriers, the frequencies of which must meet stringent orthogonality conditions [39]. It is implemented using DFT and IDFT operations. At the transmitter, user data streams undergo IDFT-based conversion to a time-domain signal via an inverse fast Fourier transform (IFFT), while the receiver employs FFT-based DFT processing to recover the transmitted signals [40], [41]. In contrast, our Q-OFDMA model replaces this classical framework with a quantum analogue that uses QFT and IQFT to encode and decode data transmitted through quantum channels. The QFT, as employed in quantum computing, transforms the amplitudes of quantum states, thereby enabling quantum-parallel processing of information.

The Q-OFDMA shown in Figure 2 depicts a simplified and typical quantum communication system with M users. It is composed of M quantum transmitters (QT) and M quantum receivers (QR). In this work, we assume the transmitters emit pure states $|\Psi\rangle$. Each user sends their quantum state into a QFT encoding operator unit. The QFT fundamentally differs from its classical DFT counterpart in its input–output representation, operational framework, and computational efficiency. While the classical discrete Fourier transform (DFT) processes a complex-valued vector $(x_0, x_1, \ldots, x_{N-1}) \in \mathbb{C}^N$ and produces a new vector $(y_0, y_1, \ldots, y_{N-1}) \in \mathbb{C}^N$ defined by the relation:

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} x_j\, \omega_N^{-jk}, \quad \text{for } k = 0, 1, \ldots, N-1, \tag{1}$$

where $\omega_N = e^{2\pi i/N}$ denotes a primitive N-th root of unity. The quantum Fourier transform (QFT) acts on a quantum superposition state:

$$|x\rangle = \sum_{j=0}^{N-1} x_j\, |j\rangle\,. \tag{2}$$

And transforms it into the state $\sum_{k=0}^{N-1} y_k |k\rangle$, where the amplitudes are given by:

$$y_k = \frac{1}{\sqrt{N}} \sum_{j=0}^{N-1} x_j\, \omega_N^{-jk}, \quad \text{for } k = 0, 1, \ldots, N-1. \tag{3}$$

When the input is a basis state $|x\rangle$, the quantum Fourier transform can be expressed as:

$$\text{QFT} : |x\rangle \mapsto \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} \omega_N^{-xk} |k\rangle. \tag{4}$$

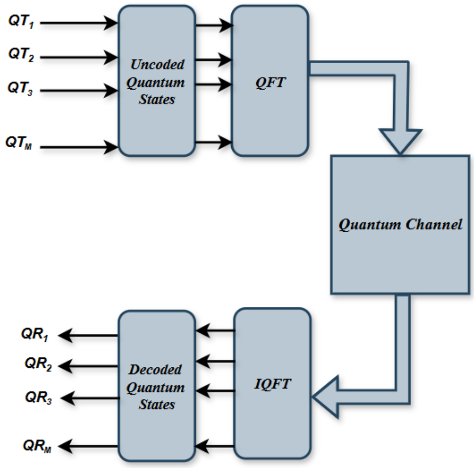

Fig. 2. quantum orthogonal frequency division multiple access scheme

The QFT output normalization includes a $1/\sqrt{N}$ factor to preserve unitarity and uses a complex exponential $\exp(2\pi ikj/N)$ consistent with quantum phase conventions. This enables the QFT to process $N = 2^n$ components simultaneously via quantum parallelism, achieving a gate complexity on the order of $O(\log^2 N)$ compared with the classical FFT's $O(N \log N)$, while preserving reversibility through unitary evolution. Following encoding, the quantum state propagates through the quantum channel, where it is inevitably subjected to a variety of quantum noise processes.

Our proposed Q-OFDMA framework can be also viewed as a centralized quantum multiplexing approach, where multiple users' data is prepared into a single quantum register. This register is processed using a QFT, which acts jointly across all qubits, enabling orthogonal allocation of the quantum spectrum to each user. The IQFT is then applied to recover each user's information with minimal interference.

B. Quantum Noise Model

In our analysis, we investigate two quantum channel models to simulate the effects of noise on quantum systems. This provides a comprehensive framework for understanding fidelity degradation in quantum communication systems. The first model is the depolarizing channel, which captures symmetric noise by replacing the input quantum state with a maximally mixed state with a specific probability, effectively eroding information uniformly across all basis states.

This channel is mathematically described by the quantum operation:

$$\mathcal{E}(\rho) = (1-p)\rho + p\frac{I}{2}, \tag{5}$$

where ρ represents the input density matrix, p is the depolarizing probability indicating the likelihood of the state being replaced by the maximally mixed state, and I is the identity operator, with the factor $I/2$ representing the maximally mixed state for a single qubit.

This model bridges a critical gap in quantum information degradation. Symmetric errors happen in all Pauli operators for isotropic noise. It offers a simple and solid tool to determine the resilience of a quantum system in the presence of unitary noise.

In the second model, we consider a scenario where we have introduced the phase-damping and depolarizing channel with random effects included to represent the uncertainty existing in practical experiments where the dominant noise mechanism could not be known exactly. This generalized noise model interpolates between phase-damping and depolarizing noise and is expressed as:

$$\mathcal{E}(\rho) = (1-p_x-p_y-p_z)\rho+p_x X\rho X+p_y Y\rho Y+p_z Z\rho Z, \tag{6}$$

where p_x, p_y, and p_z denote the probabilities of applying Pauli-X, Pauli-Y, and Pauli-Z errors, respectively, and the term $1 - p_x - p_y - p_z$ corresponds to the probability of the identity operation. The behavior of this noise model is highly flexible:

- When $p_x = p_y = p_z = p/3$, it reduces to the standard depolarizing channel, mimicking isotropic noise;
- When $p_x = p_y = 0$ and $p_z = p$, it simplifies to pure phase-damping noise, which primarily affects the phase of the quantum state (phase-flip errors);
- For intermediate values, the model allows a bias toward Z-type (phase-flip) errors while still permitting X-type (bit-flip) and Y-type (combined bit-and-phase-flip) errors, thereby capturing a broad spectrum of noise characteristics that may arise in real-world quantum implementations.

At the receiver, the IQFT is designed to reverse the effects of the QFT. Specifically, the IQFT maps a quantum state from the frequency-domain representation back to the computational-basis representation, yielding the original qubit information in the appropriate basis for subsequent measurement or further quantum processing. This reverse transformation is essential for interpreting the results of quantum computations that have been processed through the QFT. The final step in the Q-OFDMA system is a quantum process to evaluate system fidelity, which is described in the next section.

IV. SYSTEM FIDELITY

The fidelity of a quantum channel is a cornerstone for assessing the quality of quantum state transmission, quantifying the similarity between an initial state and its received counterpart after undergoing a noisy evolution. In this section, we analyze the fidelity for a bipartite quantum state under the two distinct noise models explained in the previous section. We consider a bipartite quantum state shared between the transmitted and received systems:

$$|\Psi\rangle = \sum_{ij} C_{ij} |\psi_i\rangle \otimes |\phi_j\rangle, \tag{7}$$

where C_{ij} are complex coefficients satisfying $\sum_{ij} |C_{ij}|^2 = 1$. The states $\{|\psi_i\rangle\}$ and $\{|\phi_j\rangle\}$ form orthonormal bases for the Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$ of dimensions d_A and d_B, respectively, yielding a total dimension $d = d_A d_B$.

The fidelity between the initial pure state $|\Psi\rangle$ and the output state $\rho_{\text{out}} = \mathcal{E}(|\Psi\rangle\langle\Psi|)$, where $\mathcal{E}$ is a quantum channel (completely positive trace-preserving map), is given by the overlap:

$$F(|\Psi\rangle, \rho_{\text{out}}) = \langle\Psi|\rho_{\text{out}}|\Psi\rangle. \tag{8}$$

To evaluate the performance of a channel for communication, we often consider the average fidelity over an ensemble of input states. For an ensemble of pure states $\{|\psi_j\rangle\}$ occurring with probabilities $\{P_j\}$, the average fidelity is defined as:

$$\langle F\rangle = \sum_j P_j \,\langle\psi_j|\, \mathcal{E}(|\psi_j\rangle\langle\psi_j|)\, |\psi_j\rangle. \tag{9}$$

This measure is closely related to conditional information measures used in communication theory. The depolarizing channel is defined by its action on a density matrix ρ is given in equation 5.

For any transmitted pure state $|\psi_j\rangle$, the received state is $\sigma_j = \mathcal{E}_{\text{depol}}(|\psi_j\rangle\langle\psi_j|)$. The fidelity for a transmitted state is:

$$\begin{aligned} F(|\psi_j\rangle, \sigma_j) &= \langle\psi_j| \left((1-p)|\psi_j\rangle\langle\psi_j| + p\frac{I}{d} \right) |\psi_j\rangle \qquad (10)\\ &= (1-p) + \frac{p}{d}\langle\psi_j|I|\psi_j\rangle \qquad (11) \end{aligned}$$

This indicates that the average fidelity under depolarizing noise depends solely on the error probability p and the system dimension d, a direct consequence of the channel's symmetry. For the second noise model, described in the equation 6. The total channel is the tensor product $\mathcal{E}_{\text{Pauli}} \otimes \mathcal{E}_{\text{Pauli}}$. The output state for the input $|\Psi\rangle$ is given by:

$$\rho_{\text{out}} = \sum_{k,l\in\{I,X,Y,Z\}} (p_k p_l)\,(k\otimes l)|\Psi\rangle\langle\Psi|\,(k\otimes l)^\dagger, \tag{12}$$

where $p_I = 1 - p_x - p_y - p_z$, and k, l are Pauli operators (including the identity I). The fidelity is then:

$$\begin{aligned} F &= \langle\Psi|\rho_{\text{out}}|\Psi\rangle \\ &= \sum_{k,l} p_k p_l \,\langle\Psi|(k\otimes l)|\Psi\rangle\langle\Psi|(k\otimes l)^\dagger|\Psi\rangle \\ &= \sum_{k,l} p_k p_l \,|\langle\Psi|(k\otimes l)|\Psi\rangle|^2 \,. \qquad (13) \end{aligned}$$

To evaluate this expression, we analyze the expectation values $\langle\Psi|(k\otimes l)|\Psi\rangle$. The Pauli operators (excluding identity) are traceless and have eigenvalues ±1. For a general state $|\Psi\rangle$ that is not an eigenstate of $k\otimes l$, this expectation value can be non-zero. However, a critical observation simplifies the calculation: the Pauli operators are unitary and the set $\{k\otimes l\}$ forms an orthogonal basis for operators on the Hilbert space. The expectation value $\langle\Psi|(k\otimes l)|\Psi\rangle$ represents the coefficient of the operator $k\otimes l$ in the Pauli transfer matrix representation of the state $|\Psi\rangle$. For many important states (e.g., maximally entangled states), these coefficients are non-zero only for specific k, l.

V. SIMULATION RESULTS

In this section, we show the simulation results for the performance analysis of the proposed Q-OFDMA system. A thorough simulation investigation was performed on the Qiskit platform, which provides a reliable environment for modeling quantum circuits.

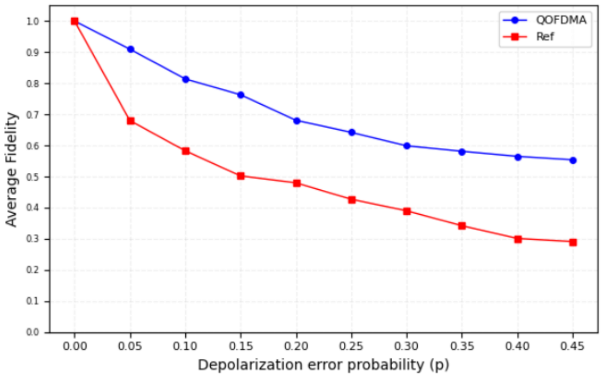

Fig. 3. Average fidelity through the depolarization channel with a fixed number of qubits.

In order to illustrate the benefits of the proposed system, a comparison was made between our Q-OFDMA model and a reference model. The Q-OFDMA model accounts for QFT before the quantum channel and IQT after it. On the other hand, in the reference model, we consider a standard scheme in which the transmission proceeds directly from the encoding stage to the channel without being converted via the QFT and IQFT. This comparative approach aims to highlight the unique characteristics of the Q-OFDMA model and evaluate its potential advantages in enhancing information fidelity compared to the conventional model.

In our work, we consider two different quantum channel models, highlighted in previous sections, which are used for simulating noise in quantum systems and offering an ample universe for understanding information loss in quantum communication systems.

In in first simulation scenario, we consider a depolarizing channel that acts as the benchmark simulating quantum information loss in an isotropic noise framework. In that model, errors are symmetric with respect to the possible Pauli operators, hence providing an easy but robust tool for the assessment of the resilience of a quantum system when subjected to uniform noise.

Figure 3 shows the performance comparisons between the proposed Q-OFDMA model and the reference model for the average fidelity, with respect to the depolarization error probability. The simulation was performed with a fixed number of qubits. It is found that in both systems, the average fidelity decreases as the probability of depolarization error increases, and this is an expected behavior as the channel noise becomes more intense. Nonetheless, the Q-OFDMA model always results in much better mean fidelity over the error probability for the given range of error probabilities that we have considered. For instance, the Q-OFDMA model here could produce an average fidelity of about 0.55 with a high error probability, whereas the reference model's fidelity is around 0.29. This great difference in performance indicates that Q-OFDMA can better tolerate depolarizing noise, illustrating the excellent performance of the introduced QFT-IQFT block to maintain quantum information fidelity in noisy channels.

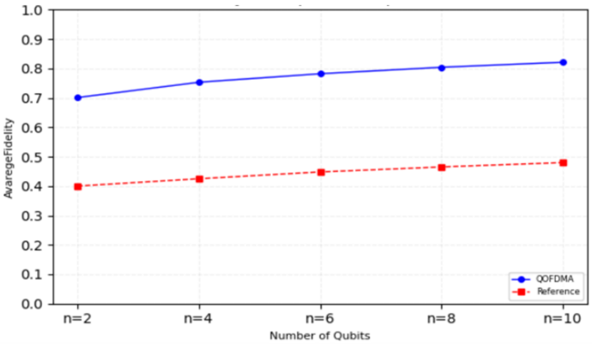

Fig. 4. Average fidelity through the depolarization channel with a fixed error probability

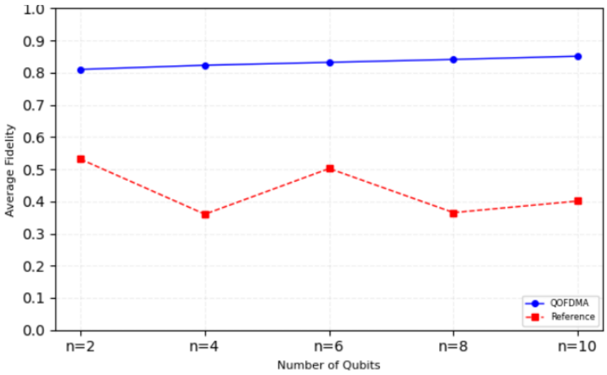

Fig. 5. Average fidelity through the second noise model

The QFT redistributes the information content of the quantum state across a superposition of basis states, preventing the concentration of information in individual qubits. Since depolarizing noise acts locally by introducing random bit and phase flips, this redistribution reduces the impact of such errors on the global quantum state. The subsequent IQFT coherently reconstructs the encoded information, leading to an effective averaging of noise effects and, consequently, higher average fidelity compared to the reference model.

Figure 4 shows the average fidelity of the Q-OFDMA model and its reference model versus the number of qubits n and the depolarization error probability fixed at 0.3. The findings confirm a definite course. For both systems, as the number of qubits increases, the average fidelity gets better.This is primarily because depolarizing noise acts locally on individual qubits, meaning each qubit is independently affected. The information is distributed across a higher-dimensional Hilbert space, which helps dilute the effects of noise. Furthermore, the use of the QFT and IQFT for encoding and decoding distributes quantum information across orthogonal basis states. This structured spreading and recovery process enhances the stability and resilience of quantum transmission. By dispersing the information throughout the quantum system, the scheme naturally averages out the effects of local noise, resulting in improved fidelity under noisy conditions.

In the second simulation scenario, we seek to test our system under more realistic, noisy conditions. This situation gives rise to a more complicated model that incorporates phase damping and depolarizing noise randomly to capture the practical uncertainties of an experimental quantum system, where we do not always have a clear idea of the dominant noise mechanism. The results shown in figure 5 indicate opposite behaviour of the two systems. The fidelity of the reference model shows an erratic behavior as a function of the number of qubits. This jittery characteristic reveals its great sensitivity to unpredictable noise types.By contrast, the QOFDMA model remains fairly consistent and consistently better than the reference model for any number of qubits. As the number of qubits increases, the fidelity of the QOFDMA system is gradually better and remains about 0.85 for n = 10. This stability demonstrates that the quantum Fourier transform (QFT)-based suppression strategy is robust against complex and uncertain noise environments. The approach is particularly valuable when the exact noise type is unknown but suspected to be phase-dominant. The underlying noise model incorporates randomness by representing errors as a tunable mixture of Pauli channels, with a bias that can be adjusted toward Z-type errors or toward a more balanced, depolarizing-like profile.

Evaluating the model's robustness across varied noise types is essential, as it confirms strong performance even under non-idealized, non-depolarizing conditions. This provides a practical and adaptable framework for real-world experiments where noise characteristics are often unknown. It would also apply when qubit counts are moderate. The model shows a consistent 30-35% fidelity advantage over conventional methods. This advantage holds across all tested conditions. It represents a significant advancement toward fault-tolerant quantum information processing.

While the proposed Q-OFDMA model demonstrates improved performance under simulated conditions, it is important to recognize its current hardware limitations. Implementing a global QFT operation over multiple user qubits requires a high degree of coherence across multi-qubit registers, which is technically demanding in today's noisy intermediate-scale quantum (NISQ) systems. Additionally, the increased gate depth introduced by QFT and IQFT operations can exacerbate gate noise accumulation, reducing fidelity in practical setups. Cross-talk between qubits and limitations in error correction further challenge scalability. Therefore, while the simulation results validate the model's theoretical performance, near-term physical realization would require significant advances in quantum hardware stability and error mitigation techniques.

VI. CONCLUSION

This work presents Quantum-Orthogonal Frequency Division Multiple Access (Q-OFDMA), a new approach to enhance the fidelity and scalability of quantum communication systems. By integrating the Quantum Fourier Transform (QFT) and its inverse (IQFT) for encoding and decoding, Q-OFDMA effectively mitigates the impact of noise and errors inherent in quantum channels. Simulations using the Qiskit platform demonstrate that Q-OFDMA outperforms the reference model across various noise scenarios, including depolarizing and generalized phase-damping channels. The system exhibits superior average fidelity, reaching up to 0.85 under complex noise conditions, and shows improved resilience as the number of qubits increases.

The findings validate the efficacy of QFT-based techniques in addressing the challenges of quantum state transmission, paving the way for practical advancements in quantum networking and computing. For future work, it would be interesting to integrate quantum error correction codes, such as surface codes and tailored codes, into the Q-OFDMA framework to enhance system fidelity under high noise conditions.

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