Enhancing Secrecy Capacity and Detection Probability in IQSC via Entanglement Purification

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***Abstract*—Integrated Quantum Sensing and Communication (IQSC) systems offer a unified platform for secure information transfer and high-precision sensing. However, their performance is fundamentally limited by entanglement degradation and channel-induced noise, which diminish both communication security and sensing accuracy. In this work, we propose a hybrid purified-IQSC (P-IQSC) architecture that incorporates Entanglement Purification Protocols (EPPs), specifically the DEJMPS protocol, to enhance entanglement fidelity and mitigate the effects of noise. The proposed framework is analytically modeled to evaluate the impact of purification on secrecy capacity and detection probability. Additional numerical simulations further validate that the P-IQSC architecture significantly outperforms conventional IQSC systems by achieving higher secrecy capacity and improved signal detection performance. These results highlight the potential of entanglement purification to enable scalable, noise-resilient quantum networks for next-generation secure sensing and communication applications.**

***Index Terms*—Entanglement Purification, P-IQSC Model, Secrecy Capacity, detection probability.**

I. Introduction

Quantum technologies are revolutionizing the domains of communication and sensing, enabling their seamless integration through the use of entangled quantum states. Quantum sensing exploits entanglement and coherence to achieve measurement precision beyond classical limits, while quantum communication ensures secure information transfer via principles such as Quantum Key Distribution (QKD), which offers theoretically unbreakable encryption [1], [2]. Recently, IQSC has emerged as a promising paradigm, allowing simultaneous environmental detection and secure data transmission within a unified quantum framework. By leveraging shared entanglement, IQSC facilitates concurrent operations such as target detection, phase estimation, and object localization alongside encrypted communication [3], [4], [4], [5].

IQSC holds considerable promise across diverse application areas, including quantum radar and secure tactical communication in defense, autonomous vehicular systems requiring joint object detection and information exchange, quantum-enhanced medical diagnostics, and future intelligent communication networks (6G and beyond). However, its real-world implementation faces significant challenges. Chief among them is the susceptibility of entangled quantum states to environmental decoherence, leading to performance degradation. These impairments reduce both secrecy capacity in communication and parameter estimation accuracy in sensing tasks [6].

Recent work by [7] presents a baseline IQSC model utilizing Einstein-Podolsky-Rosen (EPR) pairs. In their framework, one part of the entangled state is used for target interaction and sensing, while the other part supports secure communication between two parties (Alice and Bob). Their findings highlight that the secrecy capacity and detection probability are intrinsically tied to the fidelity of the shared entanglement, revealing a trade-off between these two key performance metrics. However, their model assumes ideal or near-ideal channel conditions and does not account for the entanglement degradation observed in real-world environments. To address these limitations, recent advancements have focused on Quantum Remote Sensing (QRS) and Quantum Integrated Sensing and Communication (QISAC) protocols, which leverage entangled states as shared resources for simultaneous target detection and secure information exchange [8]–[10]. In [7], a bipartite QISAC model was proposed based on EPR pairs, which demonstrates the dual-use of entanglement for both sensing and communication. Despite the promising framework, it assumes high-fidelity entanglement and overlooks the challenges posed by realistic noise, limiting its practical applicability.

In response to these challenges, various studies have explored entanglement purification techniques as a means to restore degraded entangled states by distilling high-fidelity pairs from noisy ensembles [11], [12]. While purification methods such as DEJMPS have shown effectiveness in enhancing entanglement fidelity, their integration into IQSC systems has remained relatively underexplored. To bridge this gap, we propose a P-IQSC framework that incorporates entanglement purification to restore high-fidelity entangled states prior to their use in IQSC tasks. Specifically, we employ the DEJMPS purification protocol [13], which utilizes Local operations and Classical Communication (LOCC) to distill high-quality EPR pairs from noisy channels. Our system performs purification and entanglement resource allocation, allowing the P-IQSC architecture to sustain robustness, security, and performance in realistic operating conditions.

The key contributions of this paper are as follows:

- a novel P-IQSC architecture that integrates DEJMPS-based entanglement purification.
- analytical and simulation-based evidence demonstrating significant improvements in secrecy capacity and detection probability compared to conventional IQSC systems without purification.

The remainder of this paper is structured as follows: Section II provides an overview of entanglement purification techniques, emphasizing the DEJMPS protocol and its role in fidelity enhancement. Section III introduces the proposed P-IQSC framework. Section IV outlines the entanglement purification-enhanced IQSC protocol. Section V presents the results and discussion. Finally, Section VI concludes the paper and summarizes the key contributions of the P-IQSC architecture.

II. Overview of Entanglement purification Protocols

To address the degradation of entanglement caused by noise, entanglement purification protocols such as the DEJMPS protocol [12] and recurrence methods are utilized prior to quantum sensing or communication tasks. These protocols enable two parties (Alice and Bob) to distill a smaller set of higher-fidelity entangled pairs from a noisy ensemble using LOCC. Initially, pairs with fidelity F_0 undergo one round of purification, increasing the fidelity to $F_1 > F_0$ and Multiple rounds of purification can achieve near-unity fidelity. The DEJMPS protocol plays a key role in improving fidelity in long-distance quantum communication and quantum repeaters.

The operations performed by Alice and Bob in this protocol are illustrated in Fig 1. A crucial step in the purification process is the Quantum Purification Algorithm (QPA), which is designed to purify a collection of entangled pairs, even when they are initially in a mixed state, denoted by $\hat{\rho}$. For the purification to succeed, the mixed state must have a sufficiently high fidelity with respect to at least one maximally entangled state, such as a Bell state or any state that can be transformed into a Bell state via local unitary operations. Specifically, the condition for the purification process to work is that the fidelity of $\hat{\rho}$ with respect to the class of maximally entangled states $\mathcal{B}$ must exceed $\frac{1}{2}$. This condition is mathematically expressed as:

$$\max_{\phi \in \mathcal{B}} \langle \phi | \hat{\rho} | \phi \rangle > \frac{1}{2}. \tag{1}$$

This threshold is essential because it ensures that the mixed state $\hat{\rho}$ has a strong enough correlation with a maximally entangled state, enabling local unitary operations to transform $\hat{\rho}$ into a high-fidelity maximally entangled state. If the fidelity with respect to a Bell state falls below this threshold, the state is deemed too noisy to be effectively purified. In the context of the DEJMPS protocol, this fidelity threshold guarantees that the QPA procedure, including DEJMPS, can successfully purify entangled pairs, thereby enhancing the overall quality of entanglement. This is critical for improving the performance of IQSC.

The mathematical description of entanglement purification protocol between Alice and Bob can be described as assuming that they share two noisy pairs such as Pair-1 and Pair-2 and Each pair is in a Werner state-

$$\rho = F \left|\Phi^+\right\rangle \left\langle\Phi^+\right| + (1-F)\frac{I}{4} \tag{2}$$

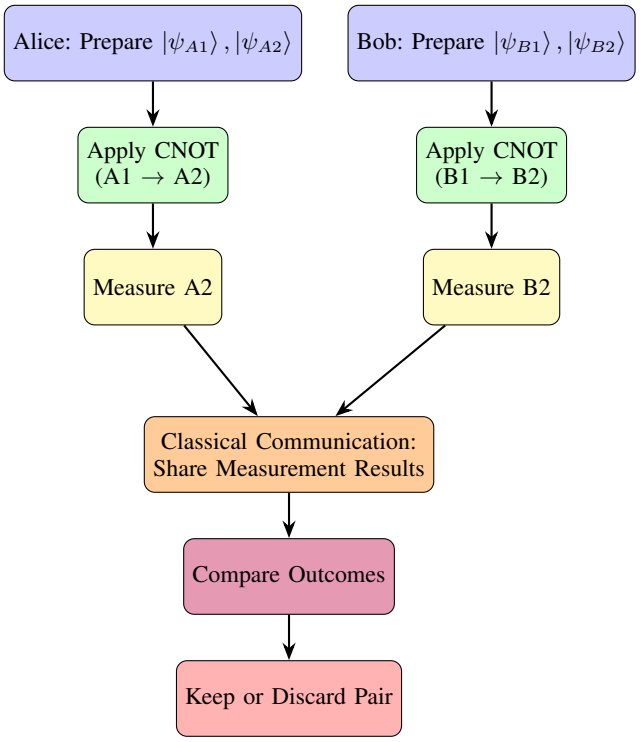

Fig. 1. Flowchart of Entanglement Purification Procedure.

where

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \tag{3}$$

Thus, initially Alice holds $A1$ and $A2$, and Bob holds $B1$ and $B2$. These are two copies of ρ. Now both Alice and Bob apply a CNOT gate, which works on *Control*- qubit $A1$ (or $B1$) and *Target*- qubit $A2$ (or $B2$). If control = 0 $\rightarrow$ target stays the same, and If control = 1 $\rightarrow$ target flips (0 $\leftrightarrow$ 1) Thus, if the initial two-qubit state is $|ab\rangle$, after applying CNOT we get

$$\text{CNOT}\,|ab\rangle = |a\rangle\,|b \oplus a\rangle\,, \tag{4}$$

where $\oplus$ denotes addition modulo 2. The action on Bell States. The four Bell states are: $|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, $|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$, $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$, $|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$. After applying CNOT (control-target across copies), the behavior is summarized in the Table I.

The measurement outcome on the target qubit reveals whether the source pair is Φ-type or Ψ-type. If we measure *0*

TABLE I
Bell States, Effect of CNOT Operations, and Error Probabilities

Initial Bell State	After CNOT	Probability
$\|\Phi^+\rangle$	$\|\Phi^+\rangle\,\|0\rangle$	F
$\|\Phi^-\rangle$	$\|\Phi^-\rangle\,\|0\rangle$	$\frac{1-F}{3}$
$\|\Psi^+\rangle$	$\|\Psi^+\rangle\,\|1\rangle$	$\frac{1-F}{3}$
$\|\Psi^-\rangle$	$\|\Psi^-\rangle\,\|1\rangle$	$\frac{1-F}{3}$

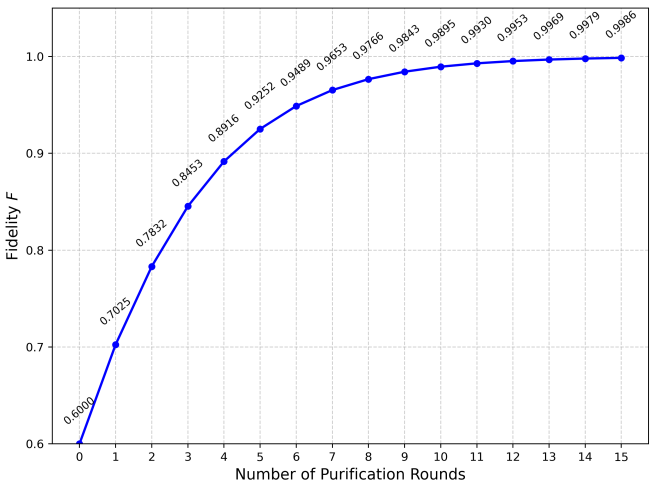

Fig. 2. Fidelity vs purification rounds.

on the target → initial Bell pair is $|\Phi^+\rangle$ or $|\Phi^-\rangle$ (good type) and If we measure *1* on the target → initial Bell pair is $|\Psi^+\rangle$ or $|\Psi^-\rangle$ (bad type). Alice and Bob measure their second qubits (targets) in the computational basis and the Outcomes will be 0 or 1. After measurement If both get *the same result* (both 0 or both 1) → *they keep the control pair* and if different → *they discard*. Thus, they post-select the entangled pairs based on measurement results.

As shown in Fig. 2, we present the fidelity improvement over successive rounds of entanglement purification using the DEJMPS protocol. Based on the initial error probabilities provided in table I. Assuming an initial fidelity $F = 0.6$, the DEJMPS protocol is applied to purify noisy Bell pairs. The purification procedure involves bilateral CNOT operations, measurement, and post-selection, where both parties retain only those outcomes where their measurement results agree. This selective retention increases the bias of the remaining states toward the desired Φ^+ Bell state.

After one round of purification, the updated fidelity F' is given by-

$$F' = \frac{F^2 + \frac{1}{9}(1-F)^2}{\left(F + \frac{1}{3}(1-F)\right)^2}. \tag{5}$$

Here, the numerator $F^2 + \frac{1}{9}(1-F)^2$ corresponds to the probability that both input pairs are in compatible Bell states—either both in Φ^+ or both in Φ^-—which leads to a correct purification outcome. The denominator, $\left(F + \frac{1}{3}(1-F)\right)^2$, represents the total probability of successful selection through post-measurement agreement. This process can be iterated. In each subsequent round, newly generated noisy pairs from the previous iteration are again subject to purification. Repeating this procedure causes the fidelity F to asymptotically approach unity. To illustrate, consider the following numerical example with an initial fidelity $F = 0.6$. Then-

$$1 - F = 0.4.$$

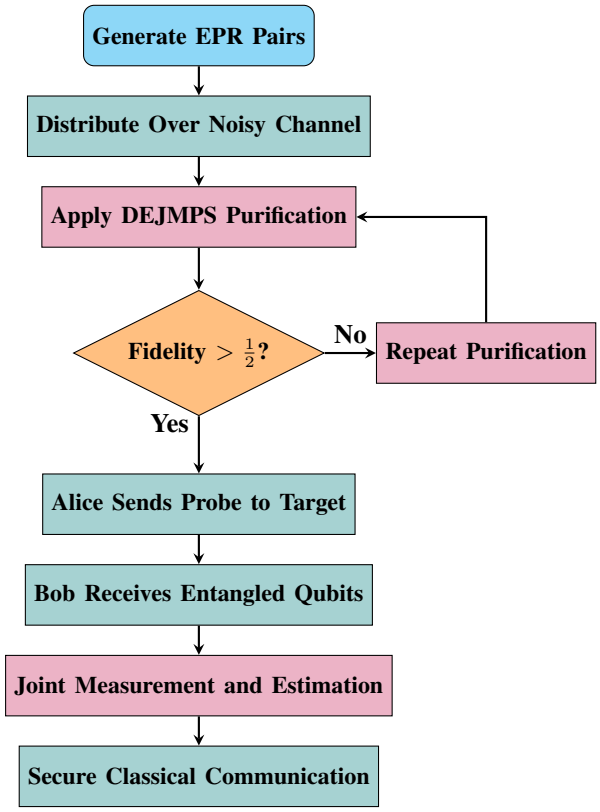

Fig. 3. Flowchart of the P-IQSC Framework

Applying Equation (5), we compute the new fidelity after the first purification round-

$$F' = \frac{0.36 + \frac{1}{9}(0.16)}{(0.6 + \frac{1}{3}(0.4))^2} = \frac{0.36 + 0.017777\ldots}{(0.6 + 0.1333\ldots)^2} \tag{6}$$

$$= \frac{0.377777\ldots}{0.537777\ldots} \approx 0.7025. \tag{7}$$

This iterative process is performed for 15 rounds. As depicted in Fig. 2, the fidelity improves with each round of purification. After 15 rounds, the final fidelity reaches:

$$\boxed{F' \approx 0.9986},$$

demonstrating the efficacy of iterative entanglement purification in driving the fidelity arbitrarily close to unity, thus enabling high-quality entangled states.

III. System Model

We consider a P-IQSC framework as shown in Fig. 3 comprising two legitimate parties, Alice and Bob, who share entangled photon pairs for the dual purposes of remote sensing and secure communication. The system utilizes EPR pairs, specifically the Bell state as shown in equation (3) which are distributed over a quantum channel subject to noise and decoherence. One photon from each pair is retained by Alice and directed toward a remote sensing interaction with a target or environment, inducing a unitary phase shift $U(\theta) = e^{-i\theta Z/2}$.

The other photon is sent to Bob for quantum correlation measurements that support secure information exchange.

The quantum channel is modeled as a depolarizing channel with depolarization probability p, such that the state ρ evolves as

$$\mathcal{E}(\rho) = (1-p)\rho + \frac{p}{3}(X\rho X + Y\rho Y + Z\rho Z), \tag{8}$$

where X, Y, Z are the Pauli matrices. This noise model captures typical imperfections in entanglement distribution, including photon loss, phase damping, and environmental decoherence. To mitigate the degradation of entanglement caused by channel noise, we incorporate the DEJMPS entanglement purification protocol [12] prior to the sensing and communication steps. The protocol enables Alice and Bob to distill a subset of higher fidelity entangled pairs from a larger, noisy ensemble using only LOCC.

Let F_0 denote the initial fidelity of the shared pairs. After one purification round, the fidelity improves to $F_1 > F_0$, albeit with a reduction in the number of surviving pairs. Repeating the purification process allows the fidelity to approach unity, provided the initial fidelity satisfies the purification threshold as mentioned in equation (1). Where $\mathcal{B}$ is the set of maximally entangled Bell states. This condition ensures that the QPA based DEJMPS procedure can successfully distill high fidelity pairs suitable for joint sensing and communication tasks. After purification, Alice transmits her purified probe qubits toward the target, which imparts a phase shift θ. Bob retains his halves of the entangled pairs. Upon receiving the reflected signal or sensing data, Alice and Bob perform joint measurements to estimate θ using phase estimation techniques (e.g., quantum Fisher information analysis) while simultaneously exploiting entanglement correlations to encode and decode classical messages securely.

IV. Proposed Entanglement Purification-Enhanced IQSC Protocol

Our framework models these improvements, quantifying secrecy, fidelity, and error rates before and after purification to assess its impact on system performance. By defining the binary entropy function, which plays a central role in calculating secrecy capacity as-

$$h(x) = -x\log_2(x) - (1-x)\log_2(1-x) \tag{9}$$

Baseline Secrecy Capacity $C_s(e)$ (Before Purification): The baseline secrecy capacity, as a function of the quantum bit error rate (QBER) e, is modeled using-

$$C_s(e) = 1 - h\left(2e(1-e)\right) - h(e). \tag{10}$$

The function $h(e)$ is the binary entropy function, which quantifies the uncertainty associated with a binary random variable. It is defined as $h(e) = -e\log_2(e) - (1-e)\log_2(1-e)$. The term $h(2e(1-e))$ specifically captures the effective probability of correlated errors that may arise due to noise in the system. To mitigate channel induced degradation, we employ one round of the DEJMPS entanglement purification protocol. The fidelity of the purified state is given by-

TABLE II
Comparison Before and After Purification

Before Purification	After Purification
$\delta^2\theta = \frac{1}{p_e \times m \times N^2}$	$\delta'^2\theta = \frac{1}{p'_e \times m \times N^2}$
$P_{\text{det1}} = 1 - \left(\frac{5+p_e}{6}\right)^{(1-p_e)m/2}$	$P'_{\text{det1}} = 1 - \left(\frac{5+p'_e}{6}\right)^{(1-p'_e)m/2}$
$P_{\text{det2}} = 1 - \left(\frac{5+p_e}{6}\right)^{k}$	$P'_{\text{det2}} = 1 - \left(\frac{5+p'_e}{6}\right)^{k}$

$$F'(e) = \frac{(1-e)^2 + \frac{e^2}{9}}{\left(1-\frac{2e}{3}\right)^2 + \frac{4e^2}{9}}. \tag{11}$$

Which quantifies the improvement in the quality of shared entanglement as a function of the initial error rate e. The probability that a pair of qubits survives the purification step is-

$$p_{\text{succ}}(e) = (1-e)^2 + 0.5e(1-e) + 0.2e^2. \tag{12}$$

That defines the trade-off between improving fidelity and the reduction in usable entangled pairs.

Final Secrecy Capacity After Purification $C_2(e)$: The secrecy capacity is recalculated using the post-purification fidelity. The final capacity is-

$$C_2(e) = p_{\text{succ}}(e) \times \left(1 - h\left(2e'(1-e')\right) - h(e')\right). \tag{13}$$

Where the effective post-purification error rate e' is given-

$$e' = 1 - F'(e). \tag{14}$$

This above formulation captures the net secrecy advantage after purification by incorporating both the fidelity gain and success probability. Finally, the improvement in sensing precision is quantified by analyzing the variance of the estimated parameter θ, denoted $\delta^2\theta_{\text{est}}$, which is inversely related to the quantum Fisher information and directly influenced by the entanglement fidelity addressed in the Table II with variance expressions derived from purified state behavior.

where $\delta^2\theta$ - variance, P_{det1} - probalility of detecting Eve against the double CNOT attack. P_{det2} - probalility of detecting Eve against general man-in-the-middle attack and p_e - ratio of photon carrying the confidential payload information. The effective probability of error becomes much *smaller*, because of the purification of DEJMPS:

$$p'_e = \alpha \times (p_e)^{2^n} \tag{15}$$

meaning that if p_e say, 0.2, now p'_e is much smaller (like p_e^2 or even p_e^4, depending on n_{rounds}). Before purification at higher p_e, the noise from the eavesdroppers increases. After purification, the effective p'_e is much smaller, the detection probability decreases for the same original p_e.

Fig. 4 effectively encapsulates the functional flow of our P-IQSC architecture, where entanglement generation, purification, and resource allocation serve as the foundation for

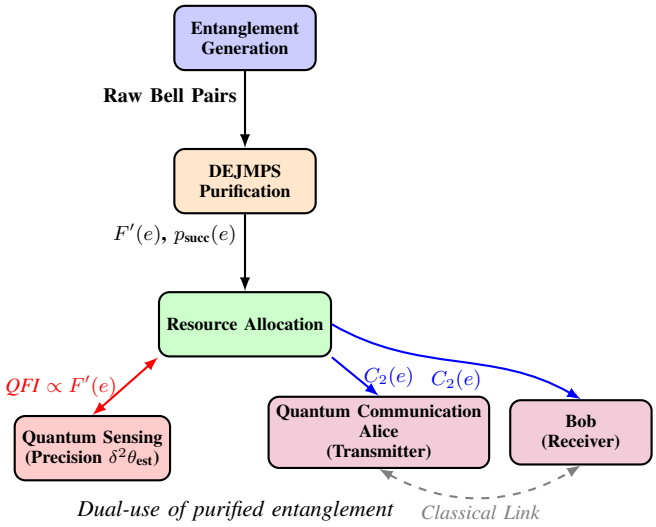

Fig. 4. P-IQSC framework showing entanglement generation, DEJMPS purification, and resource allocation for joint quantum sensing (precision $\delta^2\theta_{\text{est}}$) and secure communication (secrecy capacity $C_2(e)$).

dual-use quantum sensing and communication. Quantum fisher information (QFI) serves as a fundamental measure of how sensitively a quantum state depends on an estimated parameter, such as phase or target position. It establishes the lower bound on estimation variance via the quantum Cramér–Rao bound, where higher QFI indicates greater precision. Since QFI scales with the purity and entanglement of the quantum state, our application of the DEJMPS entanglement purification protocol plays a pivotal role. By distilling higher-fidelity Bell pairs from noisy entangled states, the purification process increases the QFI of the resulting state [14].

The DEJMPS purification module plays a pivotal role in enhancing the fidelity of entangled pairs, which directly improves both secrecy capacity and sensing precision. This is quantitatively supported by our modeling results. the initial secrecy capacity $C_s(e)$, derived from the quantum bit error rate (QBER), highlights the vulnerability of raw entanglement to noise. However, following one round of DEJMPS purification, the fidelity improves to $F'(e)$, reducing the effective error rate to $e' = 1 - F'(e)$, and leading to a significantly higher post-purification secrecy capacity $C_2(e)$, weighted by the success probability $p_{\text{succ}}(e)$.

This enhanced capacity is visually contextualized in Fig. 5, where secrecy capacity is plotted against QBER, showing the performance gap before and after purification. Moreover, the sensing subsystem in Fig. 6, benefits from improved estimation precision $\delta^2\theta_{\text{est}}$, since the variance of phase or target parameter estimation is inversely related to the quantum Fisher information, which increases with entanglement fidelity therefore, not only represents the logical flow of operations but also embodies the critical quantitative relationships that justify the inclusion of purification in both communication security and quantum sensing accuracy.

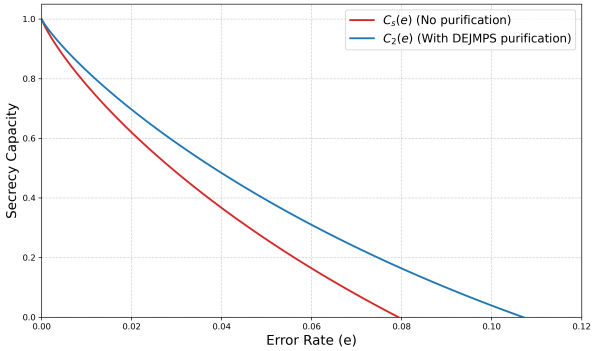

Fig. 5. Secrecy capacity vs error rate.

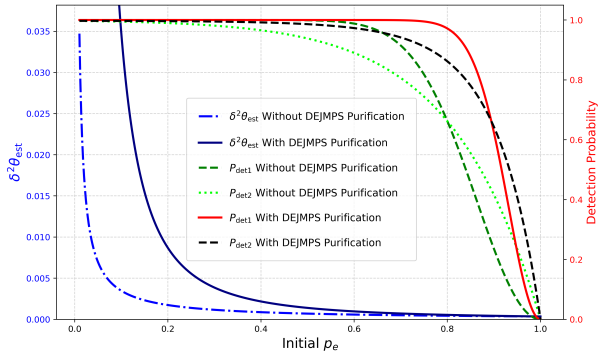

Fig. 6. Precision security trade-off with and without multiple round of DEJMPS purification.

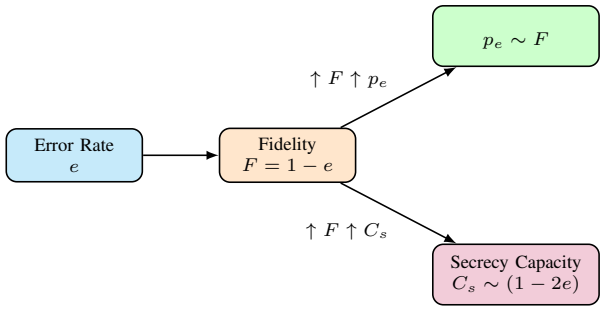

Fig. 7. Relationship between Error Rate, Fidelity, Photon Ratio Carrying Confidential Payload, and Secrecy Capacity.

V. Results and Discussion

Figures 5 and 6 collectively demonstrate the substantial benefits of applying DEJMPS entanglement purification within a IQSC framework. The analysis reveals improvements in both secrecy capacity and estimation precision under increasing levels of channel noise. Fig. 5 illustrates the behavior of the secrecy capacity C_s as a function of the channel error rate e. Without purification (red curve), the system becomes insecure beyond a critical error threshold $e_s \approx 0.080$, where $C_s \to 0$, indicating that secure communication is no longer feasible. This degradation occurs because increased noise reduces the mutual information advantage between legitimate users, allowing potential eavesdroppers to gain comparable

access to the transmitted information.

With DEJMPS purification (blue curve), the system maintains a non-zero secrecy capacity up to a significantly higher threshold, $e_2 \approx 0.107$. This enhancement is attributed to improved entanglement fidelity achieved through purification, which strengthens the quantum correlations between the legitimate parties. As a result, the mutual information gap between legitimate users and an eavesdropper is preserved over a broader noise regime, extending the secure operating range of the quantum channel. Fig. 6 addresses the precision-security trade-off by presenting the estimation variance $\delta^2\theta_{\text{est}}$ and detection probabilities P_{det1} and P_{det2} as functions of the error rate. In the absence of purification, $\delta^2\theta_{\text{est}}$ increases rapidly with noise, reflecting reduced quantum coherence and diminished phase estimation accuracy. Similarly, the detection probabilities deteriorate significantly, making signal identification unreliable. The estimation variance remains low across a wider error range, underscoring the restored quantum coherence and improved sensitivity due to higher fidelity entanglement. Additionally, the detection probabilities remain high even as the error rate increases, indicating that purified entangled states are more robust against decoherence and thus more effective in detecting weak quantum signals.

Figure 7 elucidates the relationship between error rate e, entanglement fidelity F, the proportion of photons p_e successfully delivering the confidential payload, and the resulting secrecy capacity C_s. As e decreases, the fidelity F naturally improves due to reduced decoherence. This in turn increases p_e, leading to more photons reliably transmitting secure data. The increase in fidelity also enhances the secrecy capacity C_s, reinforcing the communication system's ability to maintain confidentiality. This interplay emphasizes a key advantage of purification. By improving fidelity, it simultaneously enhances both the secure throughput and the sensing accuracy of the IQSC system. Thus, fidelity acts as a central metric linking physical-layer performance to overall system-level security and precision.

VI. Conclusion

In this work, we tackled the pressing challenge of improving the resilience and dual functionality of IQSC systems operating in noisy and decoherence prone environments. Motivated by the growing demand for secure and precise quantum technologies in emerging applications ranging from autonomous navigation and quantum radar to satellite based QKD. We proposed a novel architecture that embeds DEJMPS entanglement purification directly into the IQSC pipeline. By performing purification immediately after entanglement generation, the system proactively distills high fidelity entangled pairs before they are deployed for sensing or communication tasks. This early stage error mitigation significantly boosts the quality of the entangled resource, enabling the system to operate with improved robustness against both environmental disturbances and adversarial threats.

Through comprehensive theoretical analysis and numerical simulations, we quantified substantial improvements across multiple performance dimensions. These include enhanced quantum fidelity, extended secrecy capacity $C_s(e)$, and reduced estimation variance in quantum metrology. The model captures realistic noise conditions and accounts for purification success probability, enabling a holistic evaluation of the trade-offs between fidelity enhancement and resource overhead. The resource cost of implementing DEJMPS purification is balanced by the exponential gain in secure transmission range and sensing accuracy, making the architecture particularly suitable for scalable deployment in mobile, ground-based, or satellite-integrated quantum networks. Unlike traditional point solutions, our unified model supports joint optimization of communication security and sensing precision, thereby unlocking new capabilities in multi functional quantum platforms. Future research will explore adaptive purification strategies that respond to real-time noise fluctuations and user specific requirements.

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