Integrated Satellite-Ground Variational Quantum Sensing Networks

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The authors propose an integrated framework by combining variational quantum sensing for optimal probe preparation and dynamic utility, as well as satellite-ground quantum networking for establishing on-demand entanglement across remote terrestrial network nodes.

Abstract

Quantum sensing networks (QSNs) embody a fusion of quantum sensing and quantum communication, achieving both Heisenberg precision and unconditional security through the exploitation of quantum phenomena such as superposition and entanglement. However, the scalability and sensing capability of QSNs in the noisy intermediate-scale quantum (NISQ) era face challenges due to technological constraints, device imperfections, quantum noise, and dynamic sensing scenarios. Recent advancements in integrating quantum non-terrestrial networks (NTNs) and terrestrial networks (TNs) have paved the way for a global-scale quantum internet. Furthermore, leveraging variational quantum sensing (VQS), which capitalizes on hybrid quantum-classical computing, enhances quantum sensing capabilities. VQS tailors quantum sensing probes for dynamic sensing scenarios and noisy environments, significantly advancing application-specific NISQ sensing. We propose an integrated framework by combining VQS for optimal probe preparation and dynamic utility, as well as satellite-ground quantum networking for establishing on-demand entanglement across remote TN nodes. The integrated framework is advantageous over the standalone ground QSNs in terms of network scalability and sensing capability. Simulation results validate the effectiveness of the proposed framework, thereby introducing prospects for scalable and efficient quantum sensing on a global scale.

Introduction

Quantum sensing networks (QSNs) leverage quantum computing, sensing, and communication technologies to significantly enhance precision, sensitivity, and security in sensing applications. The integration of quantum information technologies and Internet of Things (IoT) is expected to revolutionize ultra-reliable low-latency communication, mobile edge computing, and ultra-precise network sensing by capitalizing on quantum computational intelligence, distributed quantum sensing, and quantum semantic communication [1–3]. For the classical IoT ecosystem, intelligent wireless sensor networks have emerged as a core enabling technology. However, these networks encounter networking challenges such as scalability, self-organization, security, and energy efficiency. Additionally, there are inherent limitations in the sensing capabilities of individual nodes, which include factors like precision, accuracy, resolution, sensitivity, and calibration [4].

The quantum internet will coexist with the classical internet as an additional feature and service to drive a hybrid quantum-classical (HQC) internet that benefits from quantum advantage in application-specific scenarios regarding computation, security, and sensing [5, 6]. However, quantum systems and resources are extremely sensitive to environmental fluctuations. Quantum computing aims to overcome the sensitivity of quantum systems to fully capitalize its quantum parallelism advantage, whereas quantum sensors harness the intrinsic vulnerability of quantum systems toward minuscule environmental changes to exhibit quadratic precision enhancements [7, 8]. This lays the foundation of a paradigm shift from the standalone classical IoT toward the HQC IoT wherein networks of quantum sensors collaborate to distributively sense the properties of a target system while surpassing classical limitations. However, the design goals of noisy intermediate-scale quantum (NISQ) sensing networks are strictly application-specific with severely limited practicality, scalability, and generality. Moreover, the underlying functionalities are still underdeveloped along with error-prone NISQ devices, thus limiting the achievable quantum advantage beyond classical limits [9, 10].

The envisioned structure for the global quantum internet will adopt an entangled network across terrestrial network (TN) and non-terrestrial network (NTN) nodes [11]. A significant challenge in this pursuit is establishing entanglement between distant TN nodes. Recently, free-space quantum links between NTN and TN nodes have emerged as a prospective solution to the limitations posed by optical fibers [12]. Contrarily, variational quantum sensing (VQS) harnesses HQC computing in optimizing parametrized quantum circuits (PQCs) to tailor quantum sensing probes for dynamic sensing environments. VQS outperforms both classical and quantum sensing methods by effectively mitigating quantum noise and addressing NISQ device imperfections [13]. Herein, we propose an integrated satellite-ground (or NTN-TN) HQC sensing framework incorporating VQS and the NTN-TN quantum internet. This integrated framework has advantages over standalone ground QSNs in terms of network scalabili-

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ty and sensing performance. This article:

- Details the key functional elements, design principles, and critical challenges in the design and deployment of QSNs
- Prototypes an integrated NTN-TN HQC sensing framework (Fig. 1). Herein, we identify the main components, propose the optimal VQS probe preparation, and provide remote and distributed sensing protocol variants
- Formulates a case study to showcase the potential of the proposed framework. We demonstrate the VQS advantage in achievable precision for distributed single- and multi-parameter sensing under quantum noise. We also depict the comparative advantage of utilizing satellite-ground VQS over standalone ground-based VQS.

Quantum Sensing Networks

The QSNs incorporate quantum sensing and quantum communication to achieve Heisenberg precision and unconditional security by utilizing quantum phenomena such as superposition and entanglement. In the following, we detail functional elements, design principles, and critical limitations of QSNs.

Functional Elements

Quantum resource (e.g., entanglement) management, quantum metrology techniques, and quantum sensing apparatus collectively govern the functioning of QSNs.

Entanglement Generation: Multipartite entangled states, for example, Greenberger-Horne-Zeilinger (GHZ) type states, are generated at a central node by applying entangling operations (Hadamard and controlled-NOT). The generated entangled particles are shared with each sensing node (SN) independently, by transmission using either a virtual link (preshared entanglement) or a physical link (optical fiber). Therefore, precise synchronization and coordination between QSN nodes becomes paramount to achieving high-fidelity entanglement transmission.

Entanglement Distribution: Quantum repeaters route and transmit entanglement between spatially distant nodes. This distribution is achieved through an iterative process of entanglement swapping operations among adjacent nodes. In scenarios involving extensive network coverage and noisy optical channels, entanglement distillation operations are integrated into repeaters. These operations aim to distill maximally entangled states from initially shared non-maximally entangled mixed states.

Entanglement Storage: Quantum memories consist of arrays of qubits designed to store preshared entanglement and quantum information encoded in the qubits. To accomplish this encoding, flying or communication qubits are transformed into stationary or memory qubits [3]. Various performance metrics, such as storage rate, retrieval rate, operable temperature range, and storage time, are employed to assess the storage capabilities of quantum memory units.

Quantum Metrology: Quantum metrology establishes a standardized framework for advancing quantum sensing protocols. Such protocols generally encompass the preparation of quantum sensing probes, the encoding of physical parameters — either classical or quantum — into these probes, the quantum measurement of the probe states, and the estimation of physical parameters derived from the measurement data. The metrological protocols also identify the quantum resources required to exceed classical precision limits.

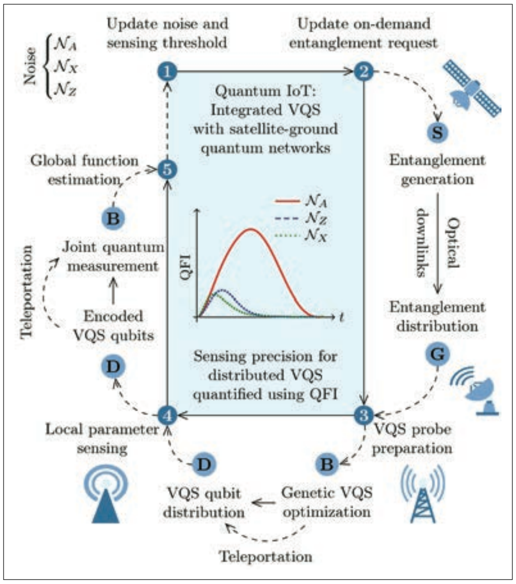

FIGURE 1. Global quantum IoT where distributed VQS is integrated within satellite-ground quantum networks. The entanglement link between TN nodes is established using on-demand entanglement requests to the satellite network. Satellites generate the entangled photon pairs and distribute them across the receiving TN nodes, that is, the base station (BS) and sensing nodes (SNs) through respective ground stations (GSs), using optical downlink transmissions. This entanglement link is utilized to transmit the optimized VQS probes from the BS to the distributed SNs. Upon receiving its corresponding qubit, each SN encodes its local parameters and transmits the encoded qubit back to BS. The BS then performs joint measurement and estimates the global functions of local parameters by processing the measurement outcomes. Herein, S, G, B, D, $\mathcal{N}_A$, $\mathcal{N}_X$, and $\mathcal{N}_Z$ denote satellite nodes, GSs, BS, distributed SNs, amplitude damping noise, bit-flip noise, and dephasing noise, respectively.

Quantum Sensors: A quantum sensor refers to a quantum system that can measure some physical properties of a system and detect environmental changes with quantum-enhanced precision and sensitivity using quantum metrology techniques. Different qubit implementations, including superconducting circuits, nitrogen-vacancy centers, trapped ions, and photonic setups, are employed to sense various physical parameters related to temperature and pressure, time, electric and magnetic fields, and displacement, respectively [7].

Design Principles

We outline the QSN architecture, performance benchmark, and salient features.

Architecture: A QSN is comprised of a central node connected to several SNs, wherein a central node generates entanglement and distributes it across SNs through quantum channels. Besides encoding physical parameters into quantum sensing probes, the SNs are locally equipped with quantum measurement devices and quantum memory units. The measurement data collected at local SNs is then communicated classically to the central node, enabling the estimation of global functions related to locally sensed parameters, such as calculating the average of local

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phase shifts for a globally synchronized network of clocks. Notably, central nodes — belonging to respective QSNs — are connected by the quantum internet, thereby rendering QSNs as subsets of the HQC IoT.

Network Analysis: The quantum Fisher information (QFI) and quantum Cramér-Rao bound (QCRB) serve as operational metrological performance indicators for QSN analysis. In scenarios where all spatial nodes sense the same quantity, inter-node entanglement emerges as a crucial resource to surpass the classical shot-noise limit and attain the Heisenberg limit. However, the inherent uncertainty tradeoffs in the precision of estimating multiple parameters create compatibility challenges among SNs, necessitating metrological resource analysis and network optimization owing to quantum advantage in distributed sensing.

Salient Features: The QSNs utilize quantum resources to outperform classical sensing networks, despite NISQ limitations. For instance, a reconfigurable entangled sensor network outperforms the shot-noise limit associated with classical sensors regarding data classification problems [14]. Furthermore, the super-Heisenberg precision scaling N^{-k} has been achieved by exploiting k-sensor interactions among N SNs, as evident from interaction-based quantum metrology experiments [8].

Critical Limitations

In the NISQ era, the potential of QSNs is critically limited due to technological incapacity in efficient design and practical deployment. The limitations are detailed as follows.

Robustness: To ensure QSNs operating at the Heisenberg limit, maintaining maximal entanglement across the network's nodes is essential. However, this entanglement is highly sensitive; even the dissociation of a single node due to local quantum noise significantly degrades overall network entanglement. The quantum research community currently faces a significant challenge in addressing the inherent fragility of qubits. This challenge includes extending qubits' coherence times, enabling their functionality at room temperature, and minimizing their susceptibility to decoherence. Consequently, it is critical to evaluate the tradeoff between the robustness and efficiency of entangled QSNs, considering their metrological utility in distributed sensing scenarios.

Networking: Dense QSNs are prone to synchronization errors among nodes and data collisions at central nodes, similar to wireless sensor networks where energy optimization is a critical concern for sustainability. Thus, robust network management and control mechanisms are crucial in both classical and quantum networks, even for standalone QSNs, to ensure the effectiveness of distributed quantum sensing within the HQC IoT framework. Furthermore, establishing access control mechanisms for multipartite entanglement facilitates on-demand connectivity, essential for maintaining reliable network coverage. VQS enhances the network's operational lifetime by leveraging quantum computing not only to refine sensing precision under noise but also to optimize resource consumption, drawing parallels to the energy efficiency goals in classical sensor networks.

Dynamic Utility: Massive HQC-IoT networks span over a large number of SNs. Maintaining multiple high-fidelity entangled sensors across these extensive networks poses a significant challenge, primarily due to the dynamic nature of noisy environmental conditions. However, limiting the number of SNs adversely impacts the overall sensing performance. The VQS framework tackles this problem through variational optimization of sensing probes, adapting to dynamic environmental fluctuations to maintain optimal sensing performance.

Scalability: Establishing entanglement over long distances requires an iterative distribution of entanglement through short distances using quantum repeaters. However, decoherence effects can deteriorate entanglement in this distribution process. Although distillation methods can address this issue to some extent, they are resource-intensive. Alternatively, entanglement distribution mechanisms with NTN-TN integration can be utilized to massively increase the scalability by limiting the use of quantum repeaters.

Based on the aforementioned challenges, integrating satellite-ground quantum networks with VQSs (Fig. 1) has the potential to enhance the resource efficiency, dynamic utility, scalability, and overall sensing capabilities of conventional QSNs. This approach includes an effective way to establish preshared entanglement across spatially distant TN nodes by utilizing NTN nodes. Moreover, the VQS utilizes NISQ computing to prepare metrologically beneficial sensing probes tailored to dynamic sensing scenarios [15].

Integrated NTN-TN HQC Sensing

Owing to the promise of effective on-demand connectivity across long distances, dynamic utility, and improved sensing performance, we prototype an integrated NTN-TN HQC sensing framework well-suited for global-scale quantum sensing services.

System Model

The key operational components of an integrated NTN-TN HQC sensing prototype are categorized as follows.

NTN Nodes: The main tasks of NTN nodes include entanglement generation and entanglement routing across NTN nodes to distribute entanglement across TN nodes. For this, NTN nodes employ satellites in lower earth orbit (LEO), medium earth orbit (MEO), and geostationary earth orbit (GEO) regions equipped with quantum communication terminals and optical terminals. Quantum communication terminals generate and manipulate entangled photons, while optical terminals consist of telescopes that transmit these entangled photons within satellite-ground entanglement distribution networks. Depending on the specificity of sensing tasks, NTN nodes are categorized as follows:

- *LEO Nodes:* LEO satellites are employed for distributed quantum sensing applications such as small-scale environmental monitoring, detecting anomalies, localization, and creating a local QSN for precise and real-time data collection.
- *MEO Nodes:* MEO satellites are employed for remote sensing, clock synchronization, regional environmental monitoring, and optimizing navigation systems.
- *GEO Nodes:* GEO satellites are well-suited for sensing tasks such as large-scale environ-

mental monitoring, global time standards, quantum global positioning systems, and relay stations for space-based quantum communications.

TN Nodes: TN nodes include base stations (BSs) as well as stationary and mobile SNs. These nodes are connected to their local ground stations (GSs) via optical fibers and linked with NTN nodes through these proximate GSs:

- *GS:* GSs are equipped with optical receivers for receiving entangled photons. These nodes control satellites and manage requests regarding entanglement routing, distribution, and storage.
- *BS:* BSs encompass HQC computational capabilities for managing complex computing tasks, control mechanisms for overseeing sensing network, and variational preparation of high-quality quantum sensing probes.
- *SN:* The sole purpose of SNs is sensing physical parameters of interest by utilizing optimal VQS probes. These nodes are also equipped with quantum memory units and quantum measurement apparatuses.

VQS Probe Preparation

Considering deleterious noisy and dynamic sensing thresholds, optimal VQS probes are tailor-made at the BS by virtue of the following process.

Initialization: The process initiates with the preparation of an N-qubit system in the state $|0\rangle^{\otimes N}$. This initial state is subsequently evolved coherently into a maximally entangled GHZ state. The transformation unfolds by applying the Hadamard gate on the first qubit and a series of controlled-NOT gates between the first qubit and each of the other qubits sequentially.

Parametrization: After establishing the maximally entangled state as the initial configuration, the next step involves the application of a PQC to tailor the trial state according to a noisy sensing scenario. The PQC design features a sequence of unitary operators, each with adjustable parameters that typically include both single-qubit and entangling gates. The single-qubit gates are responsible for adjusting the local sensor configuration, while the entangling gates are used to create quantum correlations between the sensors, which enable beyond classical sensing precision scaling. The entangling gates can be in the form of controlled unitary gates, which perform a unitary operator on a target qubit based on the state of the control qubit. This PQC is subject to an optimization algorithm to be systematically tuned for optimal performance. Note that in the initialization process, the GHZ state is prepared. This parameterization process aims to refine this GHZ state by tuning the sensor configuration based on the noise affecting the sensing process. Hence, applying the PQC on the prepared GHZ state effectively transitions the system into the intended (VQS) probe state on account of its metrological utility.

Optimization: Finding an optimal PQC is challenging given the vast search space of possible PQCs. To address this challenge, a genetic approach, inspired by the process of natural selection, is employed to heuristically explore the PQC structure for the noisy sensing task. The initiation of genetic algorithms involves generating a population of chromosomes, each intricately encoding a potential circuit structure representing the VQS probe state. The chromosomes are represented by a series of genes where each gene contains information about a unitary operator, namely, the type of quantum gate, the control qubit, the target qubit, and the adjustable parameter of the gate. For single-qubit gates, the control qubit is not defined and the gates act on the target qubit. Over a series of iterations, sophisticated genetic operators — gene deletion, insertion, replacement, swapping, and permutation — are employed to dynamically modify the chromosomes. These operators are applied randomly where the gene deletion randomly removes a series of genes within the chromosome; the gene insertion randomly inserts a newly generated series of genes in the chromosome; the gene replacement sequentially performs gene deletion and insertion operators; the gene swapping randomly swaps two randomly picked series of genes; and gene permutation randomly shuffles the genes within the chromosome. This iterative process facilitates the exploration of a diverse array of circuit structures. The fitness of each chromosome is evaluated based on the metrological utility (quantified by the QFI) of the VQS probe state emerging from these structural manipulations. The conclusion of this evolutionary process identifies the fittest PQC structure, followed by optimizing parameters (rotation angles of the gates) for the involved unitary operators. The optimization is carried out by a classical computer using either a gradient-based optimizer that employs the parameter-shift rule to calculate the gradient or a gradient-free optimizer such as constrained optimization by linear approximations (COBYLA). This meticulous refinement aims to enhance the customized sensing probes for optimal metrological performance under noisy sensing scenarios, as illustrated in Fig. 1.

Protocols

Now, we provide variational collaborative quantum sensing protocols, namely, remote VQS and distributed VQS, operating over the integrated NTN-TN HQC sensing infrastructure.

Remote VQS: This sensing protocol harnesses quantum-enhanced precision in remote areas.

Distribution: In remote sensing scenarios, the TN nodes are spatially displaced over large distances. Hence, MEO satellites are employed to establish preshared entanglement among TN nodes. The MEO satellites generate an entangled photon pair and transmit each photon of the pair to a BS and a SN, respectively. The photons are stored in quantum memory at respective locations. In this way, the end-to-end entanglement links are formulated between the BS and all SNs. Utilizing these entangled links, the BS distributes $N - 1$ VQS qubits among remote SNs through quantum teleportation.

Encoding: At the SN, the received VQS qubit interacts with target fields (physical quantities or parameters of interest). This interaction is categorized by a unitary operation in which physical parameters of the system are encoded into the VQS qubit. A notable sensing instance includes magnetic field sensing for detection and classification applications such as security, surveillance, and road safety.

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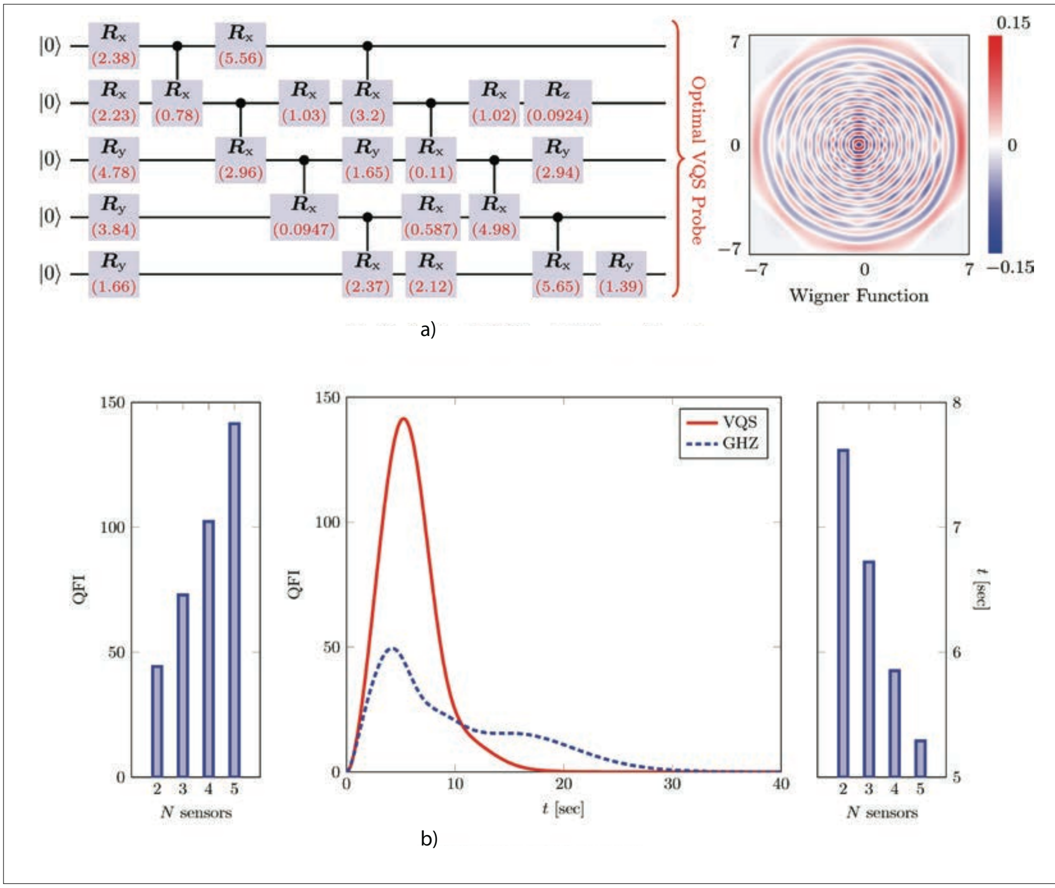

FIGURE 2. Distributed single-parameter sensing under dephasing noise at a decay rate of 0.1: a) Optimized PQC and Wigner function: The optimal PQC that maximizes QFI for the VQS probe is depicted for scalar magnetic field sensing when $N = 5$ where red values denote the optimal angle parameters of Pauli-x, -y, and -z rotation gates R_x, R_y, and R_z. The Wigner function of the optimal VQS probe state is also plotted as a function of phase-space parameters. b) Sensing performance: The QFI for optimal VQS and GHZ probes are plotted as a function of sensing time t for $N = 5$ (center). The QFI (left) and sensing time t (right) obtained for the optimal VQS probe are also depicted as a function of the number N of SNs.

Detection: After encoding, the BS and SNs locally perform quantum measurements on their respective VQS qubits. Then, all SNs send their measurement outcomes to the BS through a classical authenticated channel. By processing these outcomes, the BS remotely senses target fields at any SN with quantum-enhanced metrological sensitivity.

Distributed VQS: This sensing protocol extends cooperative quantum sensing to cover diverse geographic locations.

Distribution: In distributed sensing, the TN nodes are in close proximity, so LEO satellites are used to establish preshared entanglement links between the BS and all SNs. Then, all VQS qubits are teleported from the BS to spatially separated SNs.

Encoding: All SNs encode their local parameters in their VQS qubits. Herein, the goal is to extract the global property of a physical quantity that is usually in the form of a target field over a wide area. For example, cooperative gravitational field sensing is employed for real-time environmental monitoring applications such as underground resource mapping, infrastructure monitoring in tunnels, and predicting earthquakes.

Estimation: All SNs teleport the encoded VQS qubits back to the BS for joint measurements wherein global properties (functions of local parameters) of systems are estimated. Herein, on-demand end-to-end entangling is a primary choice due to the short coherence time for storing entangled photons in quantum memory units of TNs.

Case Study

We simulate distributed single- and multi-parameter magnetic field sensing under quantum noise. Figures 2 and 3 show the simulation results for five SNs ($N = 5$) under dephasing noise $\mathcal{N}_Z$ in single- and multi-parameter cases, respectively. Figures 2a and 3a depict the optimized PQC structures with their optimal parameter values and the Wigner functions of optimal VQS probe states. The PQC structure are synthesized using a set of single-qubit gates (Pauli-x, -y, and -z rotation gates) and a two-qubit gate (controlled Pauli-x rotation), whereas the gates composition are optimized using the genetic algorithm. Furthermore, the parameter values of PQCs are optimized using a classical optimization algorithm, which is steered by the achievable sensing precision. The Wigner function shows the non-classical behavior of the optimal VQS probe states as indicated by its negative value.

Figures 2b and 3b show the QFI achieved by the optimal VQS and GHZ probes as a function of sensing time t (center). The optimal VQS probe outperforms the GHZ probe (optimal for a noiseless scenario) as the optimal VQS state achieves a high maximum QFI value as compared to the GHZ state. The GHZ state achieves the optimal

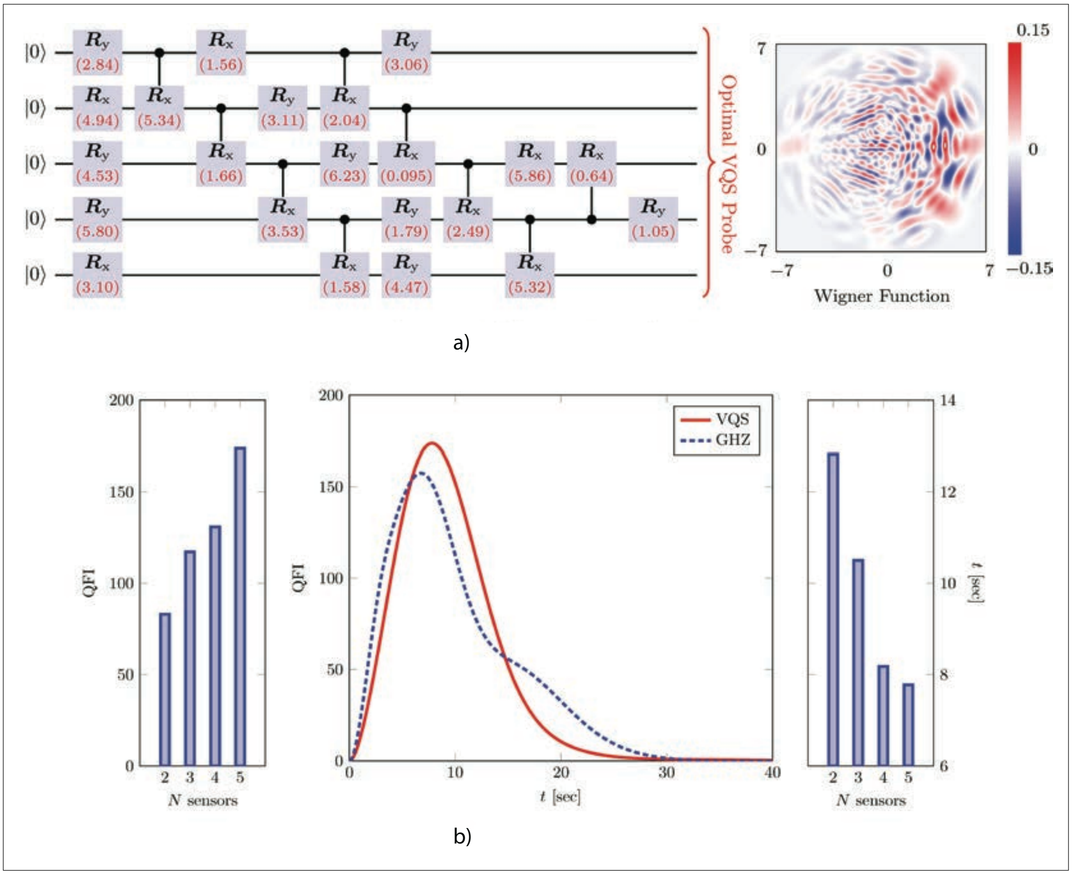

FIGURE 3. Distributed multi-parameter sensing (vector magnetic field sensing) under dephasing noise with the same parameters as in Fig. 2; a) Optimized PQC and Wigner function; b) Sensing performance.

sensing precision in a noiseless scenario due to its high sensitivity to the changes in an unknown parameter. However, its susceptibility to the noise drastically alters the state, significantly reducing its ability to detect changes in that unknown parameter. To mitigate this effect, the PQC addresses the problem by preparing a VQS probe state that navigates a trajectory within the state space, maximally accumulating the information about the unknown parameter until the metrological quality of the probe degrades. This effect is clearly visualized in Figs. 2b and 3b. The optimal VQS probe outperforms the GHZ probe as the optimal VQS state achieves a high maximum QFI value as compared to the GHZ state.

Furthermore, the performance of the optimal VQS probe is evaluated in terms of QFI (left) and sensing time t (right) for N = 2, 3, 4, and 5 (Figs. 2b and 3b). As the number N of SNs increases, the QFI increases while the sensing time t decreases. Therefore, the optimal VQS probes achieve higher sensing precision at a relatively faster rate as the QSN scale increases. It can also be seen that the probe state is more robust to amplitude damping noise as compared to the bit-flip and dephasing since these effects degrade the metrological resourcefulness of the probe state relatively fast. Furthermore, by increasing the value of the decay rate γ, the performance diminishes due to increasing noise strength per interaction time. The fact is clearly evident from Table 1 that shows QCRBs for the optimal VQS and GHZ probes under quantum noise including amplitude damping $\mathcal{N}_A$, bit flip $\mathcal{N}_X$, and dephasing $\mathcal{N}_Z$ with a decay rate of 0.1 and 0.2 when N = 2, 3, 4, 5 in distributed single- and multi-parameter sensing.

We also simulate integrated satellite-ground distributed singe-parameter VQS where an LEO satellite with an altitude of 400 km is used to establish the preshared entanglement between the BS and SNs with a variable distance between them. This is compared with a standalone ground (fiber-optic based network with 10 repeaters) VQS scenario. Figure 4 shows that the overall performance of both the aforementioned VQS scenarios decreases as the distance between the BS and SN increases due to increasing noise effects. For a comparative analysis, we plot the rate of establishing entanglement as well as entanglement fidelity (quality of virtual links) achieved by both satellite-ground and standalone ground networks. In the short-range regime (less than 500 km), the fiber-optic-based entanglement distribution exhibits better entanglement fidelity as compared to the satellite-based method (as evaluated on the NetSquid platform). However, when the distance between the BS and SN is sufficiently large, the satellite-based method exhibits far superior entanglement distribution performance. Once the preshared entanglement is established, it is utilized for probe state transmission between the BS and SNs. Figure 4 also depicts the maximum QFI value of the transmitted VQS probe states when N = 3 for both scenarios. It is noteworthy that the reduction in preshared entanglement fidelity ultimately decreases the QFI achieved by the distributed sensing probe states. Moreover,

Method	Probe	Nodes	γ = 0.1			γ = 0.2		
			$\mathcal{N}_A$	$\mathcal{N}_X$	$\mathcal{N}_Z$	$\mathcal{N}_A$	$\mathcal{N}_X$	$\mathcal{N}_Z$
Distributed Single-Parameter Sensing	VQS	2	0.08085	0.13794	0.14611	0.17790	0.31592	0.31593
		3	0.05322	0.07439	0.07459	0.11903	0.16747	0.23491
		4	0.03977	0.04639	0.04970	0.08908	0.17662	0.17835
		5	0.03325	0.03172	0.03259	0.07169	0.14223	0.14806
	GHZ	2	0.13168	0.25248	0.15555	0.57349	0.64373	0.35149
		3	0.08786	0.12014	0.12014	0.39247	0.33465	0.33465
		4	0.06434	0.08743	0.08778	0.29387	0.21434	0.26576
		5	0.05091	0.06849	0.06717	0.23369	0.27463	0.18268
Distributed Multi-Parameter Sensing	VQS	2	0.04359	0.21538	0.24583	0.09835	1.11761	1.23704
		3	0.03331	0.14225	0.15782	0.06500	0.59574	0.65099
		4	0.02524	0.11681	0.11420	0.04881	0.43080	0.43496
		5	0.01957	0.09423	0.09357	0.03895	0.37086	0.35589
	GHZ	2	0.06335	0.33968	0.37298	0.20007	1.17867	2.07283
		3	0.04792	0.17176	0.20657	0.17112	0.65935	0.90369
		4	0.03825	0.13408	0.14010	0.16432	0.63409	1.84634
		5	0.03299	0.11003	0.10447	0.13204	0.47180	0.44028

TABLE 1. QCRBs for distributed sensing (noise decay rate: γ)

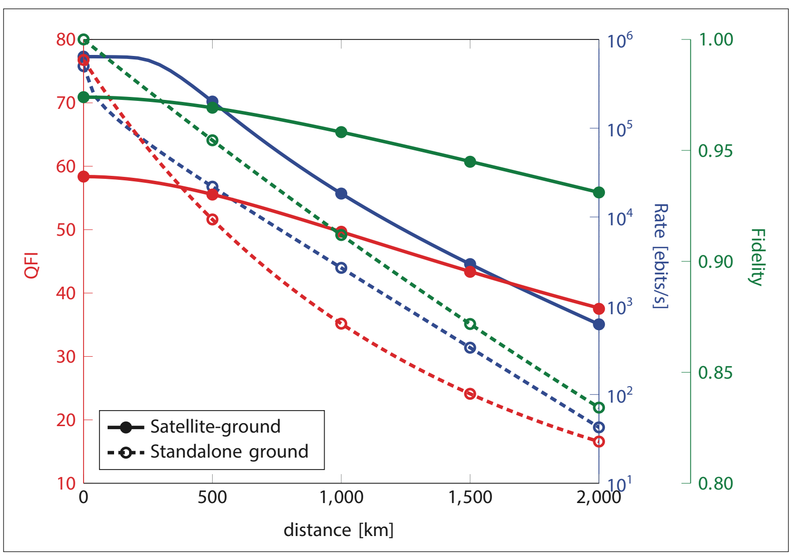

FIGURE 4. Performance comparison of integrated satellite-ground distributed single-parameter VQS with standalone ground-based VQS under dephasing noise at a decay rate of 0.1.

the maximum QFI value degrades as the distance between the BS and SN increases. However, the satellite-ground VQS outperforms standalone ground VQS under larger distance, thus marking the feasibility of implementing integrated satellite-ground VQS networks.

Conclusion

QSNs can outperform classical counterparts in terms of achievable precision and unconditional security. However, NISQ sensing networks are strictly application-specific due to limited network scalability and deleterious sensing performance under quantum noise. Integrating quantum NTN and TN lays the groundwork for the envisioned architecture of global quantum internet, establishing satellite-based mechanisms for on-demand entanglement distribution. Additionally, the VQS framework capitalizes on HQC computing to prepare optimal sensing probes robust to quantum noise. Integrated satellite-ground HQC collaborative sensing networks serve as a stepping stone in achieving scalable, secure, precise, and robust distributed and remote sensing on a global scale.

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Biographies

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