Quantum Wireless Imaging and Remote Sensing - State-of-the-Art Technologies and Opportunities

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***Abstract*—Quantum entanglement that does not exist in classic world suggests disruptive quantum image/signal processing and wireless sensing techniques beyond the frontier of classic image/signal processing and sensing. By showing the fundamental difference between classic and quantum techniques, this paper comprehensively explains the principles and mechanisms of quantum wireless ghost imaging, quantum radar, and secure quantum remote sensing, with suggestions toward future technological opportunities in communication and signal processing.**

***Index Terms*—quantum ghost imaging, ghost imaging, computational ghost imaging, quantum illumination, quantum radar, quantum remote sensing, quantum holography**

I. INTRODUCTION

Quantum information science has been widely known to revolutionize computing technology and cloud quantum computing is available in commercial market. However, there are much more technological applications that quantum technology can fundamentally contribute to advance such as notable quantum satellite (wireless) communication [1]. Among such applications, quantum wireless/remote sensing would be the subjects that researchers have paid limited attention but of high interest in engineering applications. By comprehensive explaining the unique properties of quantum entanglement, this paper overviews state-of-the-art quantum (wireless) imaging and secure quantum remote sensing technologies and highlights the technological opportunities and disruptive applications in (wireless) imaging, tomography, signal processing, sensing, radar, secure wireless/remote sensing, and potentially quantum wireless communications.

A. Quantum Entanglement and Potential in Signal Processing

Quantum mechanics governs microscopic world and thus may violate our common sense based on the experience and knowledge from macroscopic world. Heisenberg's uncertainty principle and Bohr's complementarity principle establish the theoretical foundation of quantum mechanics. For a simple computational basis $\{|1\rangle, |0\rangle\}$ in $\mathbb{C}^2$, a quantum state $|\psi\rangle$ can be represented as a probabilistic superposition $|\psi\rangle = \alpha|1\rangle + \beta|0\rangle$, where $|\alpha|^2 + |\beta|^2 = 1$. The physical realization of such computational basis, in quantum optics, can be $\{|\rightarrow\rangle, |\uparrow\rangle\}$ indicating horizontal and vertical polarizations. Bell states are the maximally entangled states of two photons (or particles in general). One of the two-photon Bell states is as follows:

$$\left|\Psi^+\right\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \qquad (1)$$

The non-separable mathematical form of a quantum state of two photons indicates quantum entanglement. Such entangled photons are typically generated by type-II SPDC [2] with a laser passing through a nonlinear crystal (NLC) to obtain output photon pairs, signals and idlers (photons). If Alice has a signal photon and Bob has an idler photon from a pair of entangled photons as (1), Alice can immediately know the quantum state of Bob's photon when she conducts the quantum measurement on her photon, which Einstein called "spooky action". From the information theoretic view of statistical signal processing, quantum entanglement supplies the possibility of extremely highly correlation among photon pairs or any particle-wave pairs, beyond classic limitation. Taking advantage of quantum entanglement may lead to many disruptive technologies in remote sensing, navigation, and wireless transmission of sensor data, which are very much wanted in future civilized or military information systems.

Quantum-entangled approach has fundamental difference from classic signal or image processing. Classic processing typically utilizes one branch of processing hardware/software in a communication channel. We can sample (in multiple times), store, duplication, filter, reconstruction, and compute the waveform samples in a deterministic manner, though the systems might be stochastic. On the other hand, quantum no-cloning theorem prohibits copying and duplication as the quantum state collapsing after quantum measurement, and classic signal processing techniques are not possible to directly create corresponding quantum signal processing techniques. Furthermore, the significant advantages of quantum entanglement innovates signal and image processing techniques by dealing with photon pairs, likely in two-branch mechanisms, which would be quite different from classic counterparts in mathematics and realizations.

B. Quantum Metrology

As a matter of fact, quantum metrology has been well known useful by physicists [3], particularly the laser interferometer gravitational-wave observatory (LIGO) to detect the gravitational waves that was recognized by the Nobel Award in Physics. Quantum metrology taking advantage of quantum mechanics greatly enhances measurement and parameter estimation of systems. Fundamentally speaking, if we conduct independent sample N times to estimate a signal in additive white Gaussian noise, the estimation error reduces proportional to $1/\sqrt{N}$. However, proper using quantum entanglement can reduce estimation error proportional to $1/N$, which implies a significant gain of $\sqrt{N}$ and extremely helpful in signal processing, (remote) sensing, localization, and navigation.

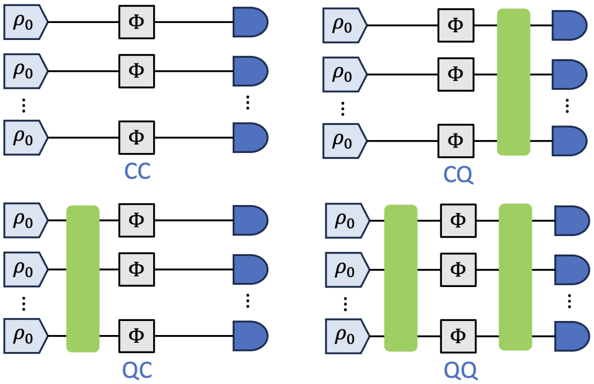

Fig. 1: Parallel Estimation Strategy [3]

Figure 1 highlights the parallel estimation strategies when quantum metrology is applied, where the green blocks indicate installing quantum entanglement. There are four strategies, the first letter indicating classic (C) or quantum-entangled (Q) realization at the transmitter end, while the second letter indicating in the same way at the receiver end. Generally speaking, quantum entangled realization would be more useful at the receiver end [3].

C. *Scope and Organization of Paper*

In this paper, we overview how to apply quantum information science, by wireless transmitting photons, to several attractive signal processing scenarios. Section II presents Ghost Imaging, particular focusing on quantum ghost imaging and computational ghost imaging, which can achieve what classic imaging cannot achieve. Section III explores quantum illumination and quantum radar, which entangled photon pairs enables advantages over classic optical radar. Section IV considers secure transmitting sensor data back to fusion center utilizing quantum entanglement and the concept of quantum key distribution.

II. GHOST IMAGING

Two-photon or correlated-photon imaging was first demonstrated in 1990's. An image could be formed by exploiting the correlation between two beams of light, while neither of them is capable of forming an image alone. Quantum entanglement assures the successful operation of two-photon imaging [4] while classical correlation could not. Correlated-photon imaging enjoys unique advantages and unusual features to create a high-resolution image, though the target object in a harsh environment and detected by low-resolution bucket photo-detector, while keeps high-resolution camera in a nice environment.

In 1995, it was discovered that if a double slit is placed in one of a pair of down conversion laser beams, no interference pattern would be formed since each beam is incoherent. However, the interference appeared when coincidence detection rate between two beams was taken into account, due to the fact that the coherence, though hidden, is still present and can be retrieved by looking both down converted photons. Such two-photon interference and diffraction effects were known as ghost interference and ghost diffraction, while ”ghost” indicates *non-local* (or ”seemingly spooky”) nature.

A. *Quantum Ghost Imaging*

Quantum ghost imaging (GI) is formed as Figure 2 [5], [6], in which spatially entangled photon pairs are generated nonlinear crystal (NLC). Signal photons illuminate the target object, through free-space wireless propagation, the photons are detected by a bucket detector D_2 as simple as a single-pixel detector. The idler photons in the reference branch are detected by spatially high-resolution device D_1. A coincidence circuit utilizes the events of D_1, D_2 detections within a short time window to reconstruct the image. Such quantum ghost imaging, a highly non-local process, can produce higher resolution and SNR than conventional imaging systems, not to mention that classic imaging system might not function in the harsh or constrained/hard-to-access environment as the shaded region in Figure 2.

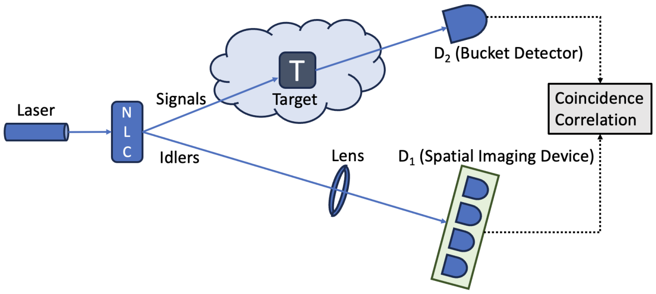

Fig. 2: Quantum Ghost Imaging System Utilizing Entangled Photon Pairs: The cloud indicates the target object in a harsh zone which is hard to effectively observe. Signal photons and idler photons transmit wirelessly.

Quantum ghost imaging by entangled photon pairs is always challenging in practical engineering facilitations and operations. In [7], ghost imaging could be carried out by using classically correlated beams to substitute entangled photon pairs. An incoherent laser beam goes through a beam splitter to create two identical copies of beam. Utilizing a rotating diffuser, these two copies moves in a spatially anti-correlated manner to reconstruct the image by intensity coincidence correlation. Such a set up to generate GI suggests the essential mechanism forming GI is the spatial momentum correlation of the photons, as the substitute functionality of quantum entanglement. Many experiments about GI were reported in literature and we could conclude that quantum GI relies on phase-sensitive cross-correlations and classical GI involves phase-sensitive and phase-insensitive correlations that adaptive optics and more efficient engineering implementation would extend technological front.

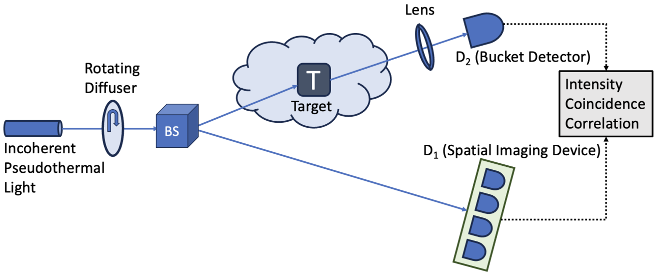

Fig. 3: Classic Optical Source to Form Ghost Imaging

A very unique aspect of quantum ghost imaging is that, though target object can be in disfavored region to observe (shaded cloud as Figure 2) with a low-complexity detector, the image can be well reconstructed with a high-resolution equipment in another region, provided the entangled photons can emit and reach. This unique feature of quantum ghost imaging and its classical realization suggests a lot of new engineering applications to facilitate, as tremendous research opportunities. Actually, not only quantum imaging, quantum holography becomes possible provided that the phase information can be properly handled. A recent example of quantum holography encodes holographic information into the second-order coherence of entangle states of light and quantifies hyper-entanglement over a huge number of modes via a spatially resolve CHSH-inequality measurement [8].

B. Computational Ghost Imaging

A disruptive way to view the quantum ghost imaging techniques was developed to form the ghost imaging under two conditions: (i) the state of input light is known (ii) the propagating path that does not contain the target object can be computed or simulated (recalling ray-tracing in radio channel modeling). Such a technology is named as *computational ghost imaging* [9], which can be set up as Figure 4. The spatial light modulator (SLM) imparts a random spatial structure responding to the light, and its spatially dependent phase shift is mathematically represented as $\phi_r(x, y)$. The reference branch as ghost imaging apparatus in Figure 2 can be substituted by the electromagnetic signal carrying information $\phi(x, y)$ fed into the computer, while the impacts due to propagation path(s) can be properly or predictively computed or simulated by the computer. Then, the computer computes the correlation function between this simulated intensity function and the measured intensity function by the bucket detector, which results in functionality analogous to the ghost imaging.

Computational ghost imaging suffers from long acquisition time to successfully reconstruct the image, and quantum ghost imaging takes even longer acquisition time. Compressive ghost imaging taking advantage of compressive (or compressed) sensing (CS) that is an efficient sampling and reconstruction technique in signal and image processing alleviates this dilemma [10]. In conventional pseudothermal GI, a target object is illuminated by a speckle field generated by a laser beam going through a rotating diffusor. For each phase realization r of the diffusor, the speckle field $I(x, y)$ which impinges on the target object is imaged accordingly. Computational ghost imaging is facilitated by splitting the laser beam to an object branch and a reference branch equipped with a CCD camera. In the object branch, the total intensity B_m transmitting through the target object is measured by a bucket detector and represented via a transmission function $T(x, y)$

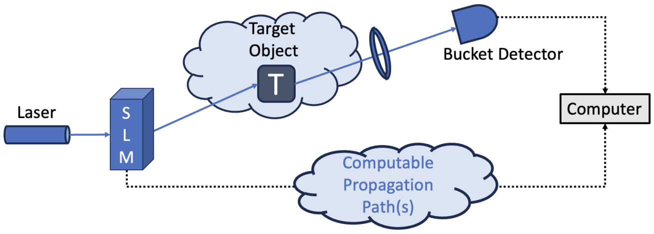

Fig. 4: Computational Ghost Imaging Mechanism

$$B_m = \int I(x, y)T(x, y)dxdy \tag{2}$$

To construct the object's transmission function $T(x, y)$, the measurements at the bucket detector are cross-correlated with the intensity patterns measured in the reference branch

$$T_{GI}(x, y) = \frac{1}{M} \sum_{m=1}^{M} (B_m - \langle B \rangle) I_m(x, y) \tag{3}$$

where $\langle \cdot \rangle = \frac{1}{M} \sum_{m=1}^{M}$ denotes an ensemble average over M realizations (or measurements). It suggests that the image is reconstructed by a linear superposition of the intensity patterns $I_m(x, y)$ with appropriate weights $B_m - \langle B \rangle$. Each measurement B_m by the bucket detector can be viewed as the overlap between the target object and the illumination pattern. Consequently, the GI measurement process can be interpreted as a vector projection of the target object transmission function $T(x, y)$ over M distinct (or different at least) random vectors $I_m(x, y)$.

The GI linear reconstruction generally proceeds without any prior knowledge on the objects. In case the number of resolution speckles (or "pixels") on the object is N, $M \geq N$ distinct intensity patterns are required to reconstruct the object, which can be viewed as the Nyquist limit of measurements in signal/image reconstruction. In practice, as these distinct intensity patterns $I_m(x, y)$ overlap, $M \gg N$ measurements are required to satisfy $SNR \gg$ 0dB. Please note that any prior information on the structure of the target object could significantly reduce the required number of measurements in the reconstruction process. Furthermore, we recall that most images are sparse (i.e. many coefficients close to zero in an appropriate basis). The fundamental idea of compressive sensing (CS) is to exploit such sparsity and reduce the required number of measurements [11].

A CS reconstruction algorithm searches for the most psarse image in the compressible basis which fulfills $M < N$ random project measurements. Applying convex optimization, we find the image $T_{CS}(x, y)$ that minimizes the L_1-norm in the sparse basis.

$$T_{CS} = \arg\min_{t} \|\Psi\{t(x, y)\}\|_{L_1} \tag{4}$$

$$s.t. \int I_m(x, y)t(x, y)dxdy = B_m, \ \forall m = 1, \cdots, M$$

where B_m are the m projection measurements and Ψ is the transform operator to the sparse basis. Above optimization in L_1-norm can be facilitated as linear programming [10].

Applying CS to computational GI extends the frontier of wireless or remote sensing technology, including utilizing quantum inspired computational imaging [12] to form imaging under the scenarios of environments not possible before, such as behind the wall, inside the body, or non-destructive inspections. Efficient GI methods and algorithms by CS and machine learning, or more precise quantum imaging, in these new application scenarios remain open to explore. [14] evaluates machine learning techniques to speed up object recognition of quantum ghost imaging, and support vector machine (SVM) shows best performance, while logistic regression suggests robust and improving performance. Appropriate machine learning appears open in engineering facilitation of quantum ghost imaging. Leveraging quantum states, privacy-preserving camera is proposed [13], and many new applications of quantum technology to engineer image processing, computer vision, and (remote) wireless transmission of images, are expected to arise.

III. QUANTUM ILLUMINATION AND QUANTUM RADAR

Radar technology has been widely applied in civil applications such as autonomous vehicles and mobile robots, in addition to traditionally aerospace and military applications. Considering the advantages of quantum metrology [3], quantum radar is surely of ultimate technological interest. In [15], Lloyd coined the concept of quantum illumination (QI) by leveraging quantum-entanglement to improve the detection capability of optical radar, even when a weakly reflecting target signal is embedded in the background noise much stronger than the returned signal. Figure 5 depicts the classic optical radar by observing reflected photons, and quantum illumination radar by collecting reflected signal photons to correlate idler photons from the entangled pairs of photons.

To comprehend the performance of QI [15], [16], a classic optical radar transmits a sequence of single-photon pulses to illuminate a region in which a weakly reflecting target is equally-likely present or absent with background light noise. The receiver makes a decision between H_1 (presence) and H_0 (absence) using minimum probability of error as the decision criterion. For QI radar, each single-photon signal is entangled with a single-photon idler. The QI receiver makes a decision according to the observation of the retained idler photons and the signal photons reflected from the interrogated region. Further crucial assumptions are

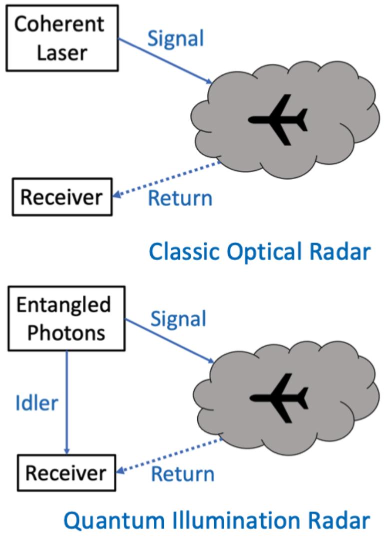

Fig. 5: Operating Principles for Classic Radars and Quantum Illumination Radars

- When the target is present, the round-trip transmitter-to-target-to-receiver portion for light beams is $0 < \kappa \ll 1$.
- The average number of background photons is N_B. $N_B \ll 1$ for low background light.
- For each transmitted photon pulse, at most one photon is collected at the receiver, regardless the presence or absence of the target, which implies $\xi N_B \ll 1$ where ξ is the time-bandwidth product of the system.

Uner good conditions (low background light), the probability of error is bounded by [16]

$$P_{e,Classic} \leq e^{-N\kappa}/2 \tag{5}$$

$$P_{e,QI} \leq e^{-N\kappa}/2 \tag{6}$$

However, QI enjoys a substantial advantage over classic optical radar, since $\kappa \gg N_B$ for classic optical radar but $\kappa \gg N_B/\xi$ for QI (good conditions extended).

Under bad conditions, the probability of error is bounded by [16]

$$P_{e,Classic} \leq e^{-N\kappa^2/8N_B}, \quad \kappa \ll N_B \tag{7}$$

$$P_{e,QI} \leq e^{-N\kappa^2\xi/8N_B}, \quad \kappa \ll N_B/\xi \tag{8}$$

QI radar is favored again due to (i) smaller κ than that of classic optical radar (ii) enjoying a factor of ξ in the exponent.

Further analysis considering a coherent state (or known as the number state) [2]. To detect a weakly reflecting $(0 < \kappa \ll 1)$ target that is equally likely present or absent with bright background light noise $(N_B \gg 1)$, the classic optical radar illuminates using a coherent state laser pulse of average number of photons as ξN_S where $N_S \ll 1, \xi \gg 1$.

QI uses entangled signal and idler pulses from SPDC of phase matching bandwidth W and duration T ($TW = \xi$), and the average number of received photons per temporal mode $N_S \ll 1$. The probability of error is bounded by [16]

$$P_{e,CS} \leq \frac{1}{2} e^{-\xi \kappa N_S / 4N_B} \tag{9}$$

$$P_{e,QI} \leq \frac{1}{2} e^{-\xi \kappa N_S / N_B} \tag{10}$$

which suggests that QI offers 6 dB enhancement over classic coherent-state optical radar.

Very recent analytical study about QI radar can be found in [17]. The remaining technical challenges lies in the analysis of further decision criterion, sequential decision process, mechanisms to fit different application scenarios. Continuous-variable quantum systems provide potentially better distance in sensing [2], and engineering realization of such systems remains an active research area. A further approach to improve quantum sensing considers distributed estimation mechanism, which leads to quantum distributed sensing [18], but more realistic operating environment shall be taken into account in future research. We may also develop quantum-inspired microwave systems to enjoy performance improvement [19] as another direction of ”quantum” remote sensing.

IV. Secure Quantum Remote Sensing

While most research interest in quantum remote sensing focuses on utilizing quantum entanglement to enhance accuracy or resolution, another emerging application scenario of interest is to transmit the data of a remote sensor in a secure manner, which is known as *secure quantum remote sensing*. Two immediate technological possibilities arise: (i) quantum cryptography, particularly well-known quantum key distribution (QKD) (ii) quantum computation to efficiently solve a classically hard problem. Blind quantum computing (BQC) strikes two at the same time, under a client-server computing architecture, while a sensor node is the client and the fusion center of a sensor network acts as the server. BQC enables a client of weak computing capability to delegate universal quantum computing to a remote server, while the client's information about data (i.e. measurement sensor data) is information theoretically protected with asymmetric information gain [20]. The client-server based quantum remote sensing proceeds as follows [20]:

1) The client sends a sample to the server which typically has high-quality sensing and computing capability. The client delegates the server to control the quantum sensor and measurement.
2) The server sends the measurement results to the client, and the server return the sample to the client.
3) After delegation, the server estimate the remaining information of the classic sample data in the server's quantum sensor.

The fundamental idea behind is useful to synthesize quantum logic gates as $|0\rangle \langle 0| \otimes \mathsf{I} + |1\rangle \langle 1| \otimes \sigma_i$, where σ_i is a Pauli matrix/operator $i = x, y, z$. Let s denote the sensor measurement and o denote the output of controlled-σ_i. The goal is to form quantum circuitry obtaining $s \oplus o$. If we conduct sensor measurements for many times, precise sensor measurement can be achieved, though low-complexity quantum remote sensor is used provided high-precision quantum sensing capability at the server, recalling ghost imaging.

In this interesting client-server quantum remote sensing architecture, classic data is exchanged. In [21], generalizing well-known quantum key distribution (QKD) is suggested to establish server's quantum control on the remote sensor measurement, to accomplish secure quantum remote sensing as Figure 6.

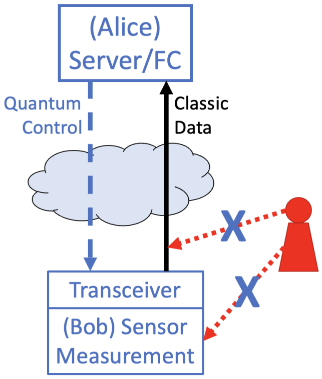

Fig. 6: Secure Quantum Remote Sensing (Eve in red)

QKD, detailed in the Appendix as the first example for quantum computing, quantum communication, and quantum cryptography, was brilliantly proposed by Bennet and Brassard in 1984 [26]. Taking advantage of quantum mechanics, the subsequent protocol is known as BB84 to establish the secret keys between Alice and Bob, which considers two bases: (a) Basis-R, rectilinear basis, $\{|\rightarrow\rangle, |\uparrow\rangle\}$ (or $\{|0\rangle, |1\rangle\}$), that is along the z-axis in the Bloch sphere. (b) Basis-D, diagonal basis, $\{|\nearrow\rangle, |\nwarrow\rangle\}$ (or $\{|+\rangle, |-\rangle\}$), that is along the x-axis in the Bloch sphere. The security of QKD is obtained from perfect randomness to select between basis-R and basis-D, and the nature of quantum measurement that can be further enhanced by quantum entanglement. The technical challenge of interest is to transmit sensor data from Bob (i.e. remote sensor) to Alice (i.e. server or fusion center) using quantum mechanics. Realizing the rationale to achieve security by QKD, the method leveraging perfect randomness and quantum entanglement [21] can be elaborated as follows, with many possible variants in system design considering rich literature regarding QKD:

1) Alice and Bob share a series of photon pairs in Bell states, with the assumption that EPR source can reliably deliver these pairs of entangled photons. The initial photon state ρ_{in} evolves to ρ_{out} by interacting environment and quantum measurement such that sensor data is securely encoded in quantum manner.
2) To calibrate the shared state, Alice and Bob randomly select a portion of shared photon pairs and collabora-

tively perform quantum state tomography. Bob sends his measurement outcomes to Alice.

3) Alice measures her remaining photons by randomly selecting between basis-R and basis-D. Such measurement outcomes are kept in secrecy. Consequently, a siingle-qubit quantum state ρ_i^B is prepared by Bob, while Alice exactly knows ρ_i^B but Eve (i.e. eavasdropper) has no information about Alice's measurement.
4) Based on the steered photon, the measurement outcome of Bob's sensing data evolves to $\tilde{\rho}_i^B$ by basis-D is sent to Alice by assuming an authenticated channel is available.
5) Knowing ρ_i^B and $\tilde{\rho}_i^B$, Alice precisely determines the sensor data/parameter but Eve cannot access the information. Please note that ρ_i^B is used as the probe state, rather than ρ_{in} to keep integrity of remote sensor data.

Please note that it is useless for Eve (red in Figure 6) to eavesdrop the classic data for the similar reason of security in QKD, not to acquire quantum sensor measurement as Eve has no information about quantum control by the server. Although the experimental setup was verified, the engineering opportunities of secure quantum remote sensing lie in potential distortion from quantum channel. For example, phase estimation techniques would enhance robustness [22]–[24], leveraging implementation improvement of QKD such as [27], and resilient/low-complexity implementation and operating protocols [25].

V. CONCLUDING REMARKS

Quantum mechanics deals with microscopic world, apart from macroscopic world that we are living. Appropriately applying quantum entanglement can greatly advance wireless imaging, radar, and remote sensing beyond what classic technology can achieve. Tremendous opportunities are available to innovate by realizing quantum information sciences to quantum information engineering in field uses.

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