Detection of Quantum Signals Free of Classical Noise via Quantum Correlation

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Extracting useful signals is key to both classical and quantum technologies. Conventional noise filtering methods rely on different patterns of signal and noise in frequency or time domains, thus limiting their scope of application, especially in quantum sensing. Here, we propose a signal-nature-based (not signal-pattern-based) approach which singles out a quantum signal from its classical noise background by employing the intrinsic quantum nature of the system. We design a novel protocol to extract the *quantum correlation* signal and use it to single out the signal of a remote nuclear spin from its overwhelming classical noise backgrounds, which is impossible to be accomplished by conventional filter methods. Our Letter demonstrates the quantum or classical nature as a new degree of freedom in quantum sensing. The further generalization of this quantum nature-based method opens a new direction in quantum research.

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Digital signal processing (DSP) and noise filtering techniques are the foundation of classical information technology [1]. These methods, such as transform-based signal processing, model-based signal processing, Bayesian statistical signal processing and neural networks, design filters based on the specific pattern of noise in either spectrum or time domain. These methods also play a crucial role in the development of quantum information science, as the separation of quantum signals from strong classical noise has wide applications ranging from quantum sensing [2–5], quantum biology [6], quantum many-body physics [7,8], and quantum computing [9]. However, these pattern-based noise filtering methods fail under various circumstances, such as pattern-less noise (white noise), or when noise is overwhelming in time or frequency domains, or strong nonstationary noise background [10]. These circumstances are common in quantum systems, as the interaction between the sensor and the quantum target is usually weak and buried by classical noises. Here, we solve this challenge with a pattern-independent and noise-free sensing of the quantum target by employing its intrinsic noncommuting quantum nature despite strong classical noises concealing the signal of the quantum target.

The signal of the classical entity can be described by a time-dependent stochastic field $B(t)$, which are always commuted to each other, namely, $[B(t), B(t')] = 0$. Therefore, conventional DSP methods can only differentiate the signal from the noise by employing different patterns between the signal and noise [upper graph of Fig. 1(a)]. In contrast to the classical entity, the signal of the quantum entity is originated from a quantum operator $\hat{B}(t)$, which acts on the quantum sensor [10–16]. The noncommuting nature of the quantum operator $\hat{B}(t)$ can generate a *quantum signal*, which is absent for the classical entity. Thus, one can use this noncommuting quantum nature of $\hat{B}(t)$ to single out the signal of the quantum target from any classical noise background, which always commutes to each other, without the requirement of any knowledge of the classical noise [lower graph of Fig. 1(a)]. It should be emphasized that the quantumness discussed here is defined as the quantumness originating from the noncommuting nature of the quantum operator $\hat{B}(t)$, which should be distinguished from the other quantumness defined in literature.

Recently, the noncommuting nature of the quantum target is quantified by a type of quantum signal derived from the time commutator of a quantum operator, which we call quantum correlation (QC) [10,17]. It was proposed that the time correlations of weak measurements could systematically extract these QCs [17] and filter out arbitrary classical noise backgrounds without resorting to their specific pattern [10]. However, the experimental realization of this weak-measurement-based approach is challenging due to its requirement on the readout properties of the quantum sensor.

In this Letter, we propose a novel protocol to extract the QC and use it to demonstrate, for the first time, removing

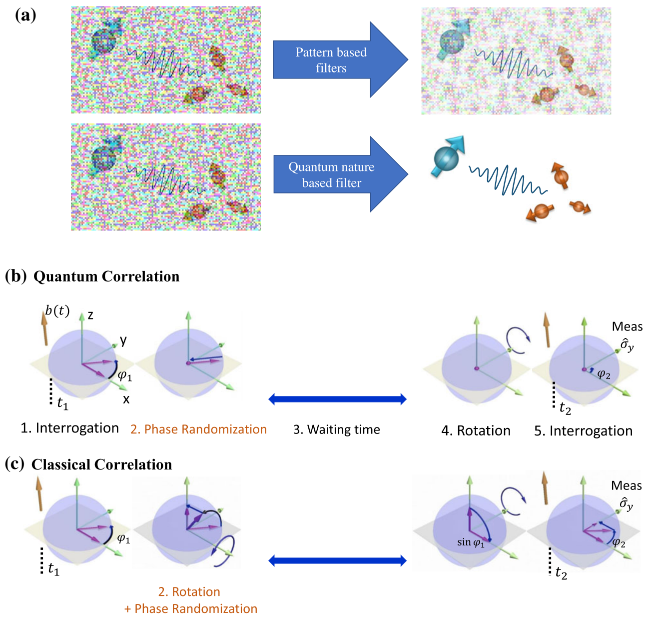

FIG. 1. Illustration of the quantum nature-based method. Comparison between traditional DSP methods which are based on pattern-dependent noise filters (upper), and the quantum-nature-based filtering method (lower). The latter can filter out arbitrary classical noise without resorting to a specific pattern of noise in the frequency or time domain. (b) The semiclassical picture of the QC protocol and (c) the semiclassical picture of the CC protocol. The difference between the QC and CC protocols is that the rotation operation is absent in the QC protocols. The final signal of these protocols is the expectation value of $\hat{\sigma}_y$ of the sensor after these operations. Phase randomization denotes the incoherent operation that eliminates the x-y components of the sensor while keeping its z components.

the classical noise background without resorting to the specific pattern of noise. In contrast to the weak-measurement-based method [10], this approach does not require multiple times of weak measurements and hence is easier to realize experimentally. By employing both coherent and incoherent operations of the sensor and only a one-time readout of the qubit, we extract an intrinsic quantum signal from a quantum target, which always vanishes in the semiclassical environment. Furthermore, we use this protocol to filter out the classical noise background and realize pattern-independent classical noise-free sensing.

The QC signal is extracted by the QC protocol as shown in Fig. 1(b). To analyze the QC signal, one needs to theoretically model the interaction between the quantum sensor and the target. The semiclassical theory [18–22] models the effects of the environment approximately via a time-dependent stochastic field. Instead, the quantum theory [11–14,23] uses quantum operators to describe the interaction between the quantum sensor and the quantum target. Below, we use both methods to analyze the QC signal.

To illustrate how the QC protocol method works, let us introduce an intuitive picture based on semiclassical theory. As shown in Fig. 1(b), a quantum sensor, modeled as a two-level system, is initialized to $|x\rangle$ and then interacts with the environment for a short time t_I [interrogation process denoted by step 1 in Fig. 1(b)]. In the semi-classical model, this environment is treated as a classical field $b(t)$ [Fig. 1(b)]. After this step, the sensor acquires a phase $\varphi_1 \approx b(t_1)t_I$ and hence the information encoded in phase φ_1 is stored in the coherence of the sensor. Then a phase randomizing step [step 2 in Fig. 1(b)] is introduced to eliminate the information stored in the phase of the sensor spin. A random phase is generated on the sensor spin on top of the original phase $\varphi_1 \approx b(t_1)t_I$ while keeping its population after this step. Therefore, all possible information about the environment encoded to the sensor in the frame of semiclassical theory is removed. As a result, the information about the environment can never be extracted no matter how the sensor is operated after this step as long as the semiclassical theory holds (e.g., if the quantum sensor is coupled with a classical field nature noise). However, in quantum theory, the entanglement between the quantum sensor and environment introduces backaction to the environment and this backaction information is also encoded in the sensor's population via this entanglement. Consequently, information about the environment can still be extracted even when phase φ_1 of the NV center has been randomized. Inspired by this idea, we introduce another interrogation step after a delay [steps 4 and 5 in Fig. 1(b)] to extract the information on how much the environment has been perturbed by the sensor in the previous steps. These steps include: a rotation by $\pi/2$ around the y direction, interaction for a duration of t_I, and measurement of the y component of sensor spin. Although from the semiclassical theory, these steps will not produce any signal as the length of the Bloch vector is 0 starting from step 2, we can still obtain a signal predicted by the quantum theory. This is the reason why this signal is called the QC signal.

Now let us investigate the QC signal in detail from quantum theory. In the interrogation process (step 1 and step 5), the sensor is coupled to a quantum bath through the Hamiltonian

$$\hat{V}(t) = \hat{S}_z \hat{B}(t),$$

while decoupled from the bath in other steps. $\hat{B}(t) = e^{i\hat{H}_B t}\hat{B}e^{-i\hat{H}_B t}$ is the time-dependent noise operator and $\hat{H}_B$ is the Hamiltonian of the bath. The total system begins with an initial state $\hat{\rho}_I = |x\rangle\langle x| \otimes \hat{\rho}_B$. As shown in Fig. 1(b), the QC signal S_Q is the expectation value of the sensor's $\hat{\sigma}_y$ in the last step. The entanglement between the sensor and bath leads to the result (see Supplemental Material [24] for details)

$$S_Q \approx -i\langle[\hat{\varphi}_2, \hat{\varphi}_1]_-\rangle/2. \tag{1}$$

Here $[]_-$ denotes the commutator and $\langle\hat{O}\rangle \equiv \mathrm{Tr}_B\{\hat{O}\hat{\rho}_B\}/2$. From this formula, S_Q can thus be attributed to the commutator of two-phase operators $\hat{\varphi}_{2(1)} \equiv t_I \hat{B}(t_{2(1)})$. Since classical phases commute to each other, the semiclassical theory always leads to vanishing QC signal S_Q. In contrast to semiclassical theory, quantum theory gives a nonvanishing signal that is proportional to the commutator of the phase operator.

Equation (1) forms the basis to remove arbitrary classical noise since it exists for a quantum entity while vanishes for any classical noise with an arbitrary pattern. If a classical noise background $b(t)$ is introduced, the noise operator $\hat{B}(t)$ is changed to $\hat{B}(t) + b(t)$. However, the commutative structure of S_Q [Eq. (1)] make the correlation of $b(t)$ absence in QC signal S_Q [10]. As a result, the QC protocol provides a pattern-independent classical noise-free detection of quantum signals.

In comparison with the QC protocol, the major difference with the classical correlation protocol [25] is that a rotation is added in step 2 before the phase randomization process [Fig. 1(c)]. This step dramatically changes the physics behind it. For the QC protocol, the phase acquired in step 1, which contains the environment information, has been eliminated by the phase randomization process in step 2 [Fig. 1(b)]. As a result, the QC protocol generates the quantum correlation signal as shown in Eq. (1). As a comparison, for the CC protocol, as shown in Fig. 1(c), the added rotation before the phase randomization process transfers the phase acquired in step 1 to the electron population to avoid being eliminated by the phase randomization process. Then this phase is correlated to the phase acquired in step 5 to generate the CC signal. Consequently, the semiclassical picture still holds in the CC protocol. The validity of the semiclassical picture is also indicated in the quantum formula of the CC signal (see Supplemental Material [24] for details):

$$S_C \approx \langle [\hat{\varphi}_2, \hat{\varphi}_1]_+ \rangle / 2, \tag{2}$$

which is related to the anticommutator of two-phase operators. As a result, if these two-phase operators are replaced by their classical correspondence $\varphi_{2(1)}$, the CC signal will recover the semiclassical results $\langle \varphi_2 \varphi_1 \rangle$ as shown in Fig. 1(c). This is the reason why it is called the CC signal. The anticommutative structure of S_C indicates that the CC signal cannot filter out the classical background $b(t)$ [10]. Equation (2) also provides a quantum origin for the classical phase picture which holds in various nanoscale NMR experiments [16,25–28].

We illustrate the noise-free detection in the context of nanoscale magnetic resonance. Here we use the QC protocol to extract the QC signal of a single nuclear spin while simultaneously filtering out arbitrary classical noise. The effective Hamiltonian of the nuclear spin takes the form of $\hat{H}_B = (\omega_0 + A_\parallel/2)\hat{I}_z$ and the coupling to the sensor is $\hat{V} = S_z[\hat{B} + b(t)]$, where $\hat{B} = A_\perp \hat{I}_x$ and $b(t)$ is arbitrary classical noise. The nuclear spin's initial state is set to be $\hat{\rho}_B = 1/2 + p_z \hat{I}_z$ and its polarization is $|p_z| \leq 1$. Equation (1) leads directly to the QC signal for short t_I:

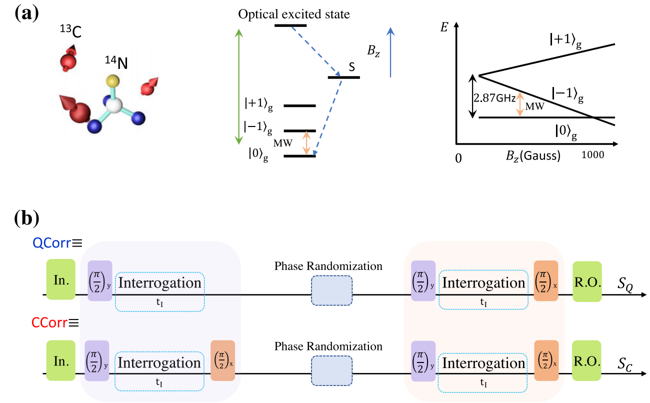

FIG. 2. Experimental implementation of the QC/CC protocol: (a) Left graph: The sketch map of the nitrogen vacancy (NV) center in diamond. The NV center is coupled with the surrounding ^{13}C nuclear spins through dipolar-dipolar interaction; The middle graph: The optical initialization and operation of the NV center; The right graph: the energy structure of the ground state of the NV center. (b) The experimental implementation of the protocol. In these pictures, the green rectangle denotes the laser pulse to initialize or read out the NV spin. The phase randomization part aims to eliminate the information on the phase of the NV center by randomizing the phase while keeping its population. It is realized by a z-direction rotation dc pulse with random rotating angles (see Supplemental Material [24]). This method can be generalized to most types of sensors. The purple (orange) rectangle denotes the $\pi/2$ microwave pulse with axis being $y(x)$.

$$S_Q \approx \frac{A_\perp^2 t_I^2}{4} p_z \sin \omega (t_2 - t_1), \tag{3}$$

where the correlation of classical noise $b(t)$ is absent. However, the CC signal S_C still contains the background induced by classical noise $b(t)$ [10].

We demonstrate this method in the system of nitrogen-vacancy (NV) center in diamond with natural ^{13}C abundance and nitrogen concentration below 3 ppb [29,30] (see experimental details in Supplemental Material [24], which includes Refs. [31–37]). As shown in the left graph of Fig. 2(a), the NV center is a negatively charged deep-level defect in diamond [29,30]. Its ground state is a spin-one system and has properties such as long coherence time, high fidelity of initialization, control and readout [29] [as shown in the middle graph of Fig. 2(a)]. It can coherently couple to its surrounding individual P1 electron spins and ^{13}C nuclear spins to form quantum computing nodes [2,38–41]; it can also be used to detect electron spins and nuclear spins in target molecules outside diamond [42,43]. Therefore, extraction of the QC signal is crucial for its further development. To demonstrate the proposed protocol, we construct a quantum sensor by isolating the subspace $|0\rangle_g, |-1\rangle_g$ of the ground states of the NV center (as shown in the right graph of Fig. 2(a). Then the protocol defined in Fig. 1(b) can be implemented using the pulse sequence shown in Fig. 2(b).

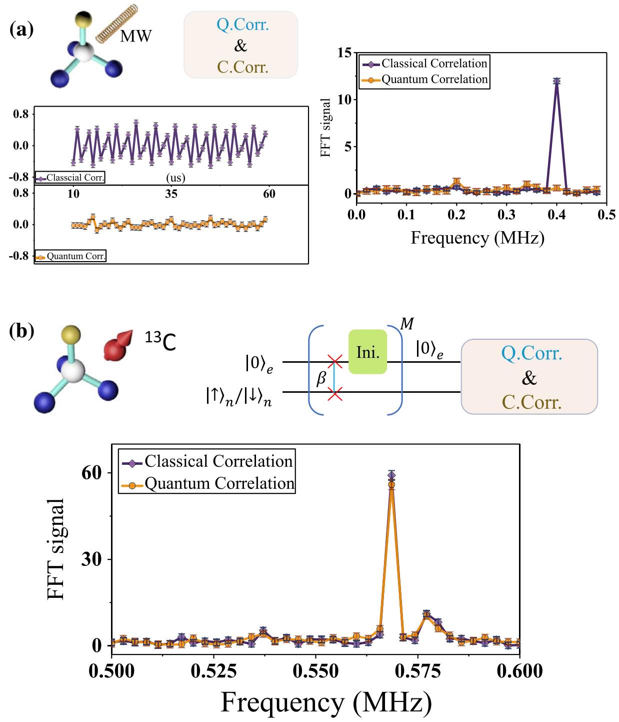

FIG. 3. Verification of the quantumness of QC signal. (a) The QC/CC signals from a sensor under the classical ac magnetic field. Left: the detected QC (orange scatters)/CC (purple scatters) correlation signals in the time domain; Right: the detected QC/CC signals in the frequency domain. (b) The QC/CC signals from a sensor coupled with nuclear spins. Upper: the sequence to measure QC/CC signal of a polarized nuclear spin. We use the method of Ref. [44] to polarize the nuclear spin bath. The electron polarization is transferred to the bath by repeating a partial swap gate (denoted by β) (see Ref. [44]). Lower: The Fourier transform of the QC/CC signal. Here the magnetic field is $B_z = 504$ G.

To verify the quantumness of the QC signal, we extract it for two different environments surrounding a quantum sensor: (1) For the classical environment (e.g., ac field), the QC signal must vanish due to the absence of intrinsic quantum noncommutability; (2) For the quantum environment, the QC signal will exist.

For the first aspect, we simulate the classical environment by an ac magnetic field from a microwave pulse. We use the pulse sequence in Fig. 2(b) to measure both the QC and CC signals of an ac magnetic field. The CC signal shows a clear peak while the QC vanishes [Fig. 3(a)]. This is expected because the classical magnetic field has no intrinsic noncommutability and hence naturally gives a vanishing QC signal [see Fig. 1(b)].

For the second aspect, we detect the QC signal from a polarized ^{13}C nuclear spin surrounding the NV center spin. Since the second-order QC signal [Eq. (3)] vanishes when the bath is in a completely mixed state, we polarize the ^{13}C nuclear spin by the method introduced in Ref. [44], where the nuclear spin polarization is transferred from the polarized electron spin by a series of engineered swap gates [upper graph in Fig. 3(b)]. In contrast to the absence of the QC signal for the ac field [Fig. 3(a)], a clear peak is found in the Fourier transform of the QC signal for the nuclear spin, which is shown in Fig. 3(b).

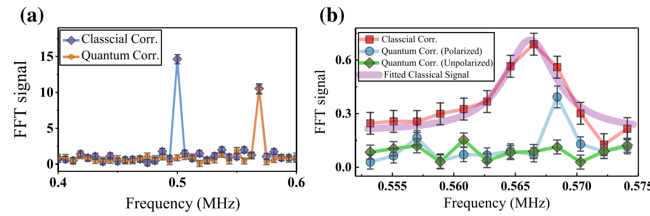

FIG. 4. The demonstration of the pattern-independent quantum sensing. (a) Filters out a single frequency classical noise. (b) Filters out classical color noise. Here the magnetic field is $B_z = 504$ G. The hyperfine coupling between the nuclear spin and sensor is 60.4 kHz.

The absence of the QC signal for classical ac signal indicates that arbitrary classical background can be filtered out by the QC protocol. In the following, we show how to detect quantum objects free of classical noise with an arbitrary pattern. We demonstrate it by detecting remote ^{13}C nuclear spins when two different artificial noises are applied to the sensor simultaneously.

The first case is a narrow bandwidth noise generated by a 500 kHz ac field at the power of −16 dbm. The bandwidth limit is 1 Hz and the detuning from target nuclear spins is 68.7 kHz. As shown in Fig. 4(a), both the target ^{13}C nuclear spin and its classical noise background occur in the CC signal while only the ^{13}C nuclear spin signal exists in the quantum one.

The second case is that the classical noise has enough spectral width (a full width 4.5 kHz at half maximum) and effective spectral strength to conceal the target signal, under which circumstance the traditional DSP methods fail. We generate this artificial color noise with a Lorentz spectrum shape as indicated by the purple curve in Fig. 4(b) (see Supplemental Material [24] for details). As shown in this figure, the peak of the CC signal is the peak of color noise [red scatters in Fig. 4(b)] instead of that of the target nuclear spin. Hence the noise buries the target signal. However, the QC signal [the blue scatters in Fig. 4(b)] clearly singles out the hidden ^{13}C nuclear spins and simultaneously filters out the classical noise background. Although the currently generated classical noise is a color noise due to the limitation of the current technique, the quantum nature-based filter method demonstrated here is, in principle, suitable for filtering white noise with infinite spectral width. Therefore this method can be especially useful for low magnetic field nanoscale NMR [45,46].

This QC protocol works much better when compared with other DSP methods. Refocusing techniques such as dynamical decoupling have been widely used in quantum research as bandpass filters. It can filter out the noise of the first case where signal and noise have different distributions, but it cannot filter out the noise of the second case as the classical noise outpowers the quantum one in the same frequency range [10]. Furthermore, traditional DSP methods such as active feedback can partially restore the linewidth, but it is usually hard to recover completely the narrow linewidth as in the case of the new method demonstrate here. Note that the linewidth of the nuclear spin signal in Fig. 4(a) and the one after the filtering in Fig. 4(b) are similar. This reflects that the QC protocol can remove the influence of stochastic classical noise completely. This complete removal and the full restoration of the linewidth are important for quantum sensing as the linewidth sets the bound of sensitivity.

The QC protocol demonstrated here has the following significance. First, major DSP methods in quantum science were adapted from the semiclassical theory, and therefore have not utilized the quantum noncommuting nature of the target signal to design the filter. As a result, the method demonstrated here gives the first quantum noncommuting-based DSP method. Second, the detection of the QC signal can also give an unambiguous identification of the quantum environment and hence gives direct experimental evidence beyond semiclassical theory. Consequently, these results demonstrate the significance of QC in the open quantum system and also its potential application in quantum control and sensing. Third, the QC protocol uses a weak-measurement-free approach to single out the quantum signal which should be absent under the semiclassical theory. Consequently, it provides a platform-universal prototype for complete characterization of the quantum environment since the multiple times weak-measurement method requires a readout technique with high fidelity and high speed [10,17]. In other words, the technique demonstrated and its potential generalization are easier to implement in a broad physical qubit system, including trapped ions or atoms, quantum dots, superconducting circuits, and defect-based systems, which are important for quantum nonlinear sensing [47].

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