Engineering asymmetric steady-state Einstein-Podolsky-Rosen steering in macroscopic hybrid systems

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I. INTRODUCTION

The observation of the “spooky action-at-a-distance” effects predicted in the famous Einstein-Podolsky-Rosen (EPR) paradox [1] is one of the most basic tests of quantum correlations. This effect was termed “steering” by Schrödinger [2]. It describes that two spatially separated systems (which are held by Alice and Bob) share an entangled state and the local measurement on one system can instantaneously affect (steer) the state of the other system [3]. In 2007, EPR steering was rigorously defined in terms of violations of a local hidden state model by Wiseman et al. [4,5]. As a class of quantum correlations, steering is a strict subset of entanglement in terms of inseparability and a strict superset of Bell nonlocality [4,6]. Moreover, steering is a directional form of nonlocality; in particular, in some scenarios one may have one-way steering, where only Alice can steer Bob, but not vice versa [4,6,7]. This is distinct from entanglement and Bell nonlocality, which are shared symmetrically between the systems.

In addition to being of fundamental interest, steering is also important to quantum networks as it provides a way to verify entanglement without requiring trust of the equipment at each node of the network; e.g., if Alice can be convinced that Bob can steer the state of her system by local measurements on his own system, then entanglement between them has been confirmed without trusting Bob’s device [4,5,8–10]. This is referred to as a one-sided (1s) device-independent (DI) protocol, an intermediate framework between the standard device-dependent approach based on state inseparability [11] and the fully DI protocol [12] based on loophole-free Bell tests. Considering the extraordinarily challenging character of the fully DI experiments, 1sDI protocols based on steering offer a more feasible approach to performing quantum secure tasks on a network where reliability or tampering of devices, dishonest observers, etc. could be an issue, e.g., 1sDI quantum key distribution [13–15], quantum secret sharing [16–18], and quantum teleportation [19–21].

Motivated both by the fundamental interest and applications, observing EPR steering in various systems and uncovering the potential of 1sDI protocols using steering as a resource [22] have attracted a great deal of attention. Experimental demonstrations of EPR steering have to date mostly been realized with optical fields [7,9,16,23–35]. Some of these experiments have shown asymmetric two-way steering [30] and even one-way steering [7,16,31–35] by producing asymmetric states via the addition of variable loss or external thermal noise to one of the subsystems. Recently, however, EPR steering has also been observed in massive, macroscopic systems such as a Bose-Einstein condensate in spin degrees of freedom [36], between an atomic ensemble and a photon [37,38], and between separated Bose-Einstein condensates [39,40]. Although the above developments represent progress toward the goal of establishing steering between nodes in a quantum network, the question remains how to realize this over appreciable distances and between potentially disparate systems as envisioned in future hybrid quantum networks [41].
In this paper, we present a scheme that deals with these challenges. It assumes that the two subsystems, between which correlations are to be generated, are connected by a propagating unidirectional light field traveling in an optical fiber (or other turbulence-free channel), a natural scenario in a quantum network. It is well known that if the two subsystems behave as harmonic oscillators with effective masses of opposite signs, then quantum correlations between them can be generated due to quantum back-action evasion in the EPR variables of the joint system [42–48]. To date, this mechanism has been successfully applied to generate entanglement between two similar objects [49–51] and to cancel quantum back action in a hybrid spin-optomechanical system [52]. Very recently, it was shown how this mechanism can be engineered to generate unconditional steady-state EPR entanglement in limited tunability to a freely tunable subsystem. Finally, we discuss the optimality and implementation of our scheme in a quantum network. It is well known that if the two subsystems are connected by a unidirectional optical field and the oscillators, the dynamics of the hybrid system can be described by the Hamiltonian [45,47] (\( \hat{H} = 1 \))

\[
\hat{H} = \hat{H}_{\text{sys}} + \hat{H}_{\text{field}} + \hat{H}_{\text{int}} + \hat{H}_{\text{diss}},
\]

where

\[
\begin{align*}
\hat{H}_{\text{sys}} &= \sum_{j \in \{+, -\}} \frac{\omega_j}{2} (\hat{X}_j^2 + \hat{P}_j^2), \\
\hat{H}_{\text{field}} &= \int_{-\infty}^{\infty} \Omega \hat{b}(\Omega) \hat{b}^\dagger(\Omega) d\Omega, \\
\hat{H}_{\text{int}} &= \sqrt{\Gamma_p} \hat{a}_L^\dagger \hat{b}(t_+) + \sqrt{\Gamma_p} \hat{a}_R \hat{b}^\dagger(t_-) + \text{H.c.}.
\end{align*}
\]

Here the optical vacuum field is described by the operator \( \hat{b}(t) \equiv \hat{b}(t) + \hat{b}_{\text{vac}}(t) = (2\pi)^{-1/2}(\int_{-\infty}^{0} + \int_{0}^{\infty}) \hat{b}(\Omega) e^{i\Omega t} d\Omega \)

\( \text{(in the frame rotating at the drive laser frequency } \omega_d) \), which is decomposed into upper and lower sideband operators \( \hat{b}_{\text{up}}(t), \hat{b}_{\text{low}}(t) \) in the time domain. The oscillator-field interaction comprises both a beam-splitter-type interaction (\( \hat{a}^\dagger \hat{b} + \text{H.c.} \)), which can generate a state transfer between the oscillator and the optical mode, and a parametric-down-conversion-type interaction (\( \hat{a}^\dagger \hat{b}^\dagger + \text{H.c.} \)), known to create squeezing and entanglement between two modes. The coefficients of the two interaction types can be parametrized as \( \Gamma_j = \Gamma_j \sin^2 \theta_j \).
\[ \Gamma_{jP} = \Gamma_j - \Gamma_{jB} \] in terms of the interaction strength \( \Gamma_j \) and the interaction angle \( \theta_j \in (0, \pi/2) \) representing the relative magnitude of the two processes, thereby controlling the type of the oscillator-field interaction. For instance when \( \theta_j = \pi/4 \), the so-called quantum nondemolition (QND) interaction is achieved (the two processes have equal weights).

Finally, the dissipation Hamiltonian \( \hat{H}_{\text{loss}} \) accounts for the decoherence processes due to the coupling of the oscillators with their individual thermal baths and the extraneous vacuum field \( \hat{b}_j \) in the presence of transmission loss \( \epsilon > 0 \).

We assume \( |\Omega_+| = |\Omega_-| \) to match the two oscillators and, for specificity, \( t_s < t_i \) for the cascade ordering, as illustrated in Fig. 1 (note that it is unimportant which of the two subsystems implements the negative mass oscillator). The unidirectional light field arriving at the second (+) subsystem then satisfies \( \hat{b}_{j,\text{in}} = e^{i\theta} \sqrt{1 - \epsilon} \hat{b}_{-\text{out}} + \hat{c}^\dagger \hat{b}_{j,\text{in}} \). Here \( \hat{b}_{j,\text{in/out}} \) is the input/output quantum field of subsystem \( j \in \{+, -\} \) and \( \hat{b}_j \) represents the uncorrelated vacuum noise due to losses that drives only the second subsystem, as depicted in Fig. 1. \( \phi \) is an adjustable quadrature rotation phase factor between the two subsystems, which we optimize numerically to minimize the EPR-steering parameter.

By performing the rotating-wave approximation (RWA) in the regime \( |\Omega_\pm| \gg \Gamma_j \geq \gamma_{\pm,0} \) and choosing the optimal quadrature \( \phi \neq 0 \), the Langevin equations after elimination of the optical field read

\[
\begin{align*}
\frac{d}{dt} \hat{a}_{-}(t) &= i(\sqrt{\Gamma_{-B}} \hat{b}_{-\text{in}} + \sqrt{\Gamma_{-P}} \hat{b}_{-\text{in}}^{\dagger}) - \frac{\gamma_{-}}{2} \hat{a}_{-} + \sqrt{\gamma_{-}} \hat{a}_{-\text{in}}, \\
\frac{d}{dt} \hat{a}_{+}(t) &= i\sqrt{1 - \epsilon}(\sqrt{\Gamma_{+B}} \hat{b}_{+\text{in}} + \sqrt{\Gamma_{+P}} \hat{b}_{+\text{in}}^{\dagger}) + i\sqrt{\gamma_{+}}(\hat{b}_{+\text{in}}^{\dagger}) \hat{b}_{+\text{in}}^{\dagger}(t') = \delta(t - t'),
\end{align*}
\]

where the total damping rate \( \gamma_{\pm} = \gamma_{\pm,0} + \gamma_{\pm,\text{opt}} \) includes the intrinsic damping rate \( \gamma_{\pm,0} \) and the dynamical optical broadening \( \gamma_{\pm,\text{opt}} \equiv \Gamma_{\pm B} - \Gamma_{\pm P} \). Dynamical stability requires \( \gamma_{\pm} > 0 \) and we will assume this condition to be fulfilled throughout the present analysis. Both oscillators are driven by the common optical vacuum input field \( \hat{b}_{\text{in}}^{\dagger} \) which has zero thermal occupation, i.e., \( (\hat{b}_{\text{in}}^{\dagger})^n(t) \hat{b}_{\text{in}}^{\dagger}(t') = \delta(t - t') \), as does the extraneous vacuum field \( (\hat{b}_{\text{in}}^{\dagger})^n(t) \hat{b}_{\text{in}}^{\dagger}(t') = \delta(t - t') \). In addition, both oscillators are coupled to their individual thermal reservoirs with expectation values given by \( (\hat{b}_{\pm,\text{in}}^{\dagger})^\dagger \hat{b}_{\pm,\text{in}}^{\dagger}(t') = (\bar{n}_{\pm,0}) + 1) \delta(t - t') \), where \( \bar{n}_{\pm} \) are the mean thermal occupation numbers, inducing the thermal decoherence rates \( \bar{\gamma}_{\pm,0} \equiv \gamma_{\pm,0} \bar{n}_{\pm,0} + 1/2 \). In terms of these, we introduce the quantum cooperativities \( C_j = \Gamma_j/\bar{\gamma}_{j,0} \) of the subsystems, i.e., the ratio of the coherent coupling and thermal decoherence rates, which will play a prominent role in the analysis below. Note that this definition of quantum cooperativity in terms of the rate \( \Gamma_j = \Gamma_{jB} + \Gamma_{jP} \) differs from that typically used in optomechanics [56] (except in the resolved-sideband regime).

The unidirectional light field will (in general) read out the response of the first oscillator (−) and map this information to the second oscillator (+), thereby inducing an effective directional coupling of the first to the second oscillator with the rate \( R = \sqrt{\Gamma_{-P}^{1}\Gamma_{+P}^{1} - \Gamma_{-B}^{1}\Gamma_{+B}^{1}} = -\sqrt{\Gamma_{+B}^{1}\sin(\theta_{+} - \theta_{-})} \). This directional coupling arises whenever the interaction angles of the two oscillators differ from each other \( \theta_{+} \neq \theta_{-} \), so that \( R \neq 0 \). This coupling provides an additional mechanism for building correlations (in addition to the common optical bath) that allows us to control the asymmetry of EPR steering and enhance the steerabilities, as will be explored below.

Integrating Eqs. (3) from the initial time \( t_0 = -\infty \) to \( t \) leads to solutions from which the variances and covariances of the quadratures operators \( \hat{X}_\pm, \hat{P}_\pm \) (defined relative to the classical amplitudes, respectively) can be evaluated. These steady-state values within the RWA are [53]

\[
\begin{align*}
\langle \Delta \hat{X}_0 \rangle^2 &= \langle \Delta \hat{P}_0 \rangle^2 = \frac{\Gamma_{+}/2 + \bar{\gamma}_{-0}}{\gamma_{-}}, \\
\langle \Delta \hat{X}_\pm \rangle^2 &= \langle \Delta \hat{P}_\pm \rangle^2 = \frac{\Gamma_{+}/2 + \bar{\gamma}_{\pm0} + 2\sqrt{1 - \epsilon R \bar{n}}(\hat{X}_+, \hat{X}_-)}{\gamma_{+}}, \\
\langle \hat{X}_+, \hat{X}_- \rangle &= -\langle \hat{P}_+, \hat{P}_- \rangle = -\sqrt{1 - \epsilon}[\sqrt{\Gamma_{+} + \bar{\gamma}_{+}} \sin(\theta_{+} + \theta_{-}) - 2R(\Delta \hat{X}_0)^2] / \gamma_{+} + \gamma_{-},
\end{align*}
\]

where we use the notations \( (\Delta \hat{x})^2 \equiv \langle \hat{x}^2 \rangle - \langle \hat{x} \rangle^2 \) and \( \langle \hat{x}, \hat{y} \rangle \equiv \langle (\hat{x}^2) + (\hat{y}^2) \rangle/2 - \langle \hat{x} \rangle \langle \hat{y} \rangle \).

### III. EPR-STEERING CRITERION

We now present the criterion for having EPR-steering correlations in our system. The presence of EPR steering can be detected by adopting Reid’s EPR criterion [9,60], which is expressed in terms of the product of the inferred uncertainties for the quadrature variables. EPR steering from the first (−) to the second (+) oscillator is confirmed if

\[
E_{+/-} = \Delta_{\text{inf}} \hat{X}_+ \Delta_{\text{inf}} \hat{P}_+ < \frac{1}{2}.
\]

Here, \( \Delta_{\text{inf}} \hat{X}_+ \equiv \Delta(\hat{X}_+ - \bar{g}_+ \hat{X}_-) \) and \( \Delta_{\text{inf}} \hat{P}_+ \equiv \Delta(\hat{P}_+ + \bar{g}_+ \hat{P}_-) \) are the inferred uncertainties in the prediction for the values of the second (+) oscillator’s position and momentum based on the outcomes of the local measurements performed on the first (−) oscillator, where \( \bar{g}_+ \) and \( \bar{g}_- \) are arbitrary real constants, adjusted to minimize the inferred uncertainties. For Gaussian states and measurements, as is the case here, Eq. (5) is necessary and sufficient to detect EPR steering [4,9]. The smallness of the steering parameter \( E_{+/-} \) gives a measure of the Gaussian steerability from the first (−) to the second (+) subsystem. Ideally, it becomes zero when the two oscillators are in a perfect EPR state where the position and momentum of the second (+) oscillator can be predicted with 100% accuracy, based on the measurements performed on the first (−) oscillator.

From Eqs. (4), we have the optimal value \( \bar{g}_+ = \bar{g}_- = \bar{g}_0 = (\bar{X}_+ + \bar{X}_-)/(\langle \Delta \hat{X}_0 \rangle^2) \) within the RWA, obtained by the variation method \( \delta \Delta_{\text{inf}} \hat{X}_+ (\hat{P}_+) / \delta \bar{g}_0 (\bar{g}_0 = 0) \). Hence, the minimized inferred quadrature variances are \( (\Delta_{\text{inf}} \hat{X}_+)^2 = (\Delta \hat{X}_0)^2 - (\langle \hat{X}_+, \hat{X}_- \rangle / (\Delta \hat{X}_0)^2) \), \( (\Delta_{\text{inf}} \hat{P}_+)^2 = (\Delta \hat{P}_0)^2 - (\langle \hat{P}_+, \hat{P}_- \rangle / (\Delta \hat{P}_0)^2) = (\Delta_{\text{inf}} \hat{X}_0)^2 \), such that the
steering figure of merit (5) minimized within the RWA reads
\[ E_{+/-} = (\Delta_{\text{int}} \hat{X})^2 = (\Delta \hat{X})^2 - (\langle \hat{X}_+ \rangle \langle \hat{X}_- \rangle)^2/(\langle \Delta \hat{X} \rangle^2). \] (6)

Note that the inferred quadrature variance (6) are composed of two terms: The first is the noise in the subsystem to be steered, and the second is the uncertainty reduction achieved by measuring the other, correlated subsystem.

The criterion for EPR steering in the opposite direction, i.e., the first (−) oscillator is steered by the measurements performed on the second (+) oscillator, follows from swapping the + and − subscripts in the above expressions, yielding
\[ E_{-/+} = (\Delta_{\text{int}} \hat{X}_-)^2 = (\Delta \hat{X}_-)^2 - (\langle \hat{X}_- \rangle \langle \hat{X}_+ \rangle)^2/(\langle \Delta \hat{X}_- \rangle^2). \] (7)

The system exhibits two-way steering when simultaneously \( E_{+/-} < 1/2 \) and \( E_{-/+} < 1/2 \). If only one of them is satisfied, it is referred to as one-way steering.

IV. ASYMMETRIC STEERING CONTROL

We first study the distinctive feature of EPR steering, i.e., the asymmetric correlation distribution between the two subsystems. From Eqs. (4), we can write down the EPR-steering parameters (6) and (7) as
\[ E_{+/-} = (\Delta \hat{X}_+)^2 - (\langle \hat{X}_+ \rangle \langle \hat{X}_- \rangle)^2 = \frac{1}{(\Delta \hat{X}_0)^2} \left[ \frac{1}{1 - \epsilon f} - \sqrt{1 - \epsilon f} \right] (\Delta \hat{X}_+)^2, \]
\[ E_{-/+} = (\Delta \hat{X}_-)^2 - (\langle \hat{X}_- \rangle \langle \hat{X}_+ \rangle)^2 = \frac{1}{(\Delta \hat{X}_0)^2} \left[ \frac{1}{1 - \epsilon f} + \sqrt{1 - \epsilon f} \right] (\Delta \hat{X}_-)^2, \] (8)

where \( f = 2R/\gamma_+ \) is a parameter associated with the additional noise interference due to the induced directional coupling. In Eqs. (8), we have used the substitution \( (\Delta \hat{X}_0)^2 = (\Delta \hat{X}_0)^2 + \sqrt{1 - \epsilon f} \langle \hat{X}_+, \hat{X}_- \rangle \), where
\[ (\Delta \hat{X}_0)^2 \equiv \left( \gamma_+ / 2 + \gamma_{+,0} / \gamma_+ \right) / \gamma_+ \] (9)

represents the bare variance of the second (+) oscillator, which has the same form as \( (\Delta \hat{X}_+)^2 \equiv (\Delta \hat{X}_-)^2 \) \[ \text{[Eq. (4)]} \], composed only by the light back action and its thermal noise, and is thus independent of the correlations between the subsystems. From Eqs. (8), we see that the steering parameters include two parts: the bare variance of each subsystem \( (\Delta \hat{X}_0)^2 \) and the noise reduction \( \propto (\langle \hat{X}_+, \hat{X}_- \rangle)^2 \) due to the correlations between the subsystems. When the two subsystems are coupled to the optical field with the same interaction angles \( \theta_+ = \theta_-, \text{ i.e., } f = 0 \), the asymmetry of steering in the steady state solely depends on the difference of the bare variances in the two subsystems, which are determined by their individual cooperativities \( C_\pm \) and decoherence properties \( (\gamma_{\pm,0}, \bar{n}_{\pm,0}) \).

Once the interaction types of the two subsystems with the optical field become asymmetric \( \theta_+ \neq \theta_- \), i.e., \( f \neq 0 \), the induced directional coupling of the first (−) to the second (+) subsystem will affect both the covariance \( (\hat{X}_+, \hat{X}_-) \) and the quadrature variance \( (\Delta \hat{X}_+)^2 = (\Delta \hat{X}_0)^2 + \sqrt{1 - \epsilon f} \langle \hat{X}_+, \hat{X}_- \rangle \) of the second (+) subsystem, giving rise to the additional nontrivial asymmetry of the two steering parameters \( E_{+/-} \) and \( E_{-/+} \) manifest in Eqs. (8); this offers an extra, tunable channel to asymmetrically control EPR steering between the two subsystems within the scheme.

To study the asymmetric steering that can be engineered via this additional channel, we will in the following often assume identical decoherence parameters \( (\gamma_{\pm,0} = \gamma_0, \bar{n}_{\pm,0} = \bar{n}) \) of the subsystems to exclude the asymmetry brought about by differing thermal parameters. We will show how to efficiently control the degrees and directions of EPR steering by tuning the cooperativities \( C_\pm \) and interaction types \( \theta_{\pm} \) of each subsystem with regard to the unidirectional optical field.

A. Tuning quantum cooperativities

First, we show how to engineer the asymmetry of EPR steering by tuning the quantum cooperativities \( C_\pm \) of each subsystem for different choices of fixed interaction angles, taking \( \theta_+ = 0.35\pi \) and considering the three cases \( \theta_+ = 0.35\pi \), \( \theta_+ = 0.5\pi \), \( \theta_+ = 0.4\pi \), respectively.

The contour plots in the left column of Fig. 2 show the regions in the \((C_-, C_+)\) plane in which there exists two-way steering (white region), one-way steering for which \( E_{+/-} < 0.5 < E_{-/+} \) (light pink region), and the opposite direction of one-way steering where \( E_{+/-} < 0.5 < E_{-/+} \) (dark blue region). We remark that similar regions of steering are found when assuming instead that the thermal baths of the hybrid
system are in the vacuum state, using the parameters values $\gamma_0 = 2\pi \times 20 \text{ kHz}$ and $\bar{n} = 0$, resulting in approximately the same decoherence rate $\gamma_{0}$ as considered in Fig. 2.

The results indicate that tuning the quantum cooperativities of the subsystems plays different roles in controlling the directions of EPR steering under the three situations where $f = 0$ ($\theta_{+} = \theta_{-}$), $f > 0$ ($\theta_{+} = \theta - 0.05\pi$), and $f < 0$ ($\theta_{+} = \theta + 0.05\pi$). For the parameters considered here, when the two subsystems are driven optically only by the common vacuum field ($f = 0$), two-way steering occurs for reasonably large quantum cooperativities, i.e., $C_{\pm} > 10$, while the range of one-way steering is negligible, as shown in Fig. 2(a). The reason is in this case that the asymmetry of steering builds up purely due to the difference of the bare variances of the two subsystems, i.e., $(\Delta X_{\pm})^2$ in Eqs. (8), which are only determined by the difference of $C_{\pm}$ for the two subsystems. In the region where EPR steering appears, the asymmetry brought about by this difference is small. Distinct asymmetric steering appears in the presence of asymmetric noise interference in the two steering parameters as induced by the unidirectional coupling ($f \neq 0$). As illustrated in Figs. 2(c) and 2(e), both one-way steering in the direction ($- \Rightarrow +$) (light pink region) and in the opposite direction ($+ \Rightarrow -$) (dark blue region) can be achieved by suitably tuning the values of $C_{\pm}$ depending on the sign of $f$. In addition, two-way steering (white region in the middle) still exists when $0.40 \lesssim C_{+}/C_{-} \lesssim 1.7$ for $f > 0$ and $0.45 \lesssim C_{+}/C_{-} \lesssim 3.2$ for $f < 0$.

The precise values of the steering parameters $E_{+|-}$ (dashed) and $E_{-|+}$ (solid) are depicted in the right column of Fig. 2 as a function of $C_{+}$ for fixed $C_{-} = 50$, corresponding to vertical cuts in the respective contour plots. Since in the decomposition of Eqs. (8), the steering parameters $E_{+|-}$ and $E_{-|+}$ are composed of the bare variance and the noise reduction due to the correlation, we also plot the curves of $(\Delta X_{\pm})^2$ (thin orange, dashed) and $(\Delta X_{\pm})^2$ (thin orange, solid) as a function of the ratio $C_{+}/C_{-}$ to show this contribution to the steering parameters. These curves reflect the dynamical cooling of the oscillators relative to their thermal equilibrium occupancy $\bar{n}_{\pm,0}$ as can be seen from Eq. (9) when $\gamma_{\pm} > \gamma_{\pm,0}$. The bare variance $(\Delta X_{\pm})^2$ is decreased (better dynamical cooling) with increasing cooperativity $C_{\pm}$ for a fixed $\theta_{\pm} > \pi/4$, as shown in the right column of Fig. 2, and its asymptote for large $C_{\pm}$ is the limit imposed by the finite degree of sideband asymmetry of the oscillator-light coupling as parameterized by $(\pi/4) \leq \theta_{\pm} \leq (\pi/2)$. In the fully asymmetric limit, $\theta_{\pm} = \pi/2$, the bare variance can be cooled to the ground state, i.e., $(\Delta X_{\pm})^2 = 1/2$, when $C_{+} \gg 1$ (referred to as the “fully-resolved-sideband limit” in the context of optomechanics).

For the performance of EPR steering, in the case of $f = 0$ shown in Fig. 2(b), the steerableities in the two directions are approximately equal in the range of $C_{+} \gg 1$. This can be understood by introducing the ratio of the steering parameters, which can be expressed using Eqs. (8) as

$$
\frac{E_{+|-}}{E_{-|+}} = \frac{(\Delta X_{+})^2}{(\Delta X_{-})^2} \approx \frac{\gamma_{+}^2 + \sqrt{-1 - \epsilon f(\hat{X}_{+}, \hat{X}_{-})}}{(\Delta X_{-})^2}.
$$

When $f = 0$ (i.e., $\theta_{\pm} = \theta$), the ratio of the steering parameters is equal to the ratio of the bare variances, which are both approximately equal to $-1/[2\cos(2\theta)]$ when optical broadening dominates $\gamma_{\pm} \approx \gamma_{\pm,0}$ and cooperativities are large $C_{\pm} \gg 1$. However, for the cases of $f \neq 0$ as shown in Figs. 2(d) and 2(f), the steerableities in the two directions become obviously asymmetric. The reason for this asymmetry of steering can be seen from Eq. (10), where the ratio of the steering parameters now depends not only on the different degrees of the dynamical cooling (\(\theta_+ \neq \theta_-\)) but also on the asymmetric noise interference in the two steering parameters resulting from the unidirectional coupling ($f \neq 0$). Specifically, when $f > 0$ [Fig. 2(d)], $E_{+|-} > E_{-|+}$ with the parameters studied here, making one-way steering possible only in the direction from the second ($+$) to the first ($-$) subsystem. In contrast, for the case of $f < 0$ [Fig. 2(f)], we find four regions of steering with increasing $C_{+}/C_{-}$: no steering, one-way steering from the second ($+$) to the first ($-$), two-way steering, and again one-way steering in the opposite direction, indicating that the asymmetry of steering can be controlled more flexibly via tuning the quantum cooperativities $C_{\pm}$ when $f < 0$.

**B. Tuning interaction angles**

We now show the behavior of EPR steering as a function of interaction angles $\theta_{\pm}$ for fixed values of $C_{+} = 50$ and $2C_{-} = 100$. As illustrated in Fig. 3, for the parameters considered here, one can find suitable ranges of $\theta_{\pm}$ to realize both one-way and two-way steering. To be specific, when $C_{+} = 50$, two-way steering (white region) and one-way steering in the direction $+ \Rightarrow -$ (dark blue region) can be achieved by tuning $\theta_{\pm}$, as shown in Fig. 3(a). However, when $C_{+} = 2C_{-} = 100$
[Fig. 3(c)], one-way steering in both the direction + ⇒ −
(dark blue region) and − ⇒ + (light pink region) become
possible by tuning θ… and θ…, respectively, and
these regions meet near the crossing points θ… ≈ θ… (i.e.,
f ≈ 0). Note that similar regions of EPR steering in the
(θ…, θ…) plane are found if instead assuming the subsystems
to be coupled to vacuum thermal baths, i.e., if the thermal
parameters are assumed to be γ₀ = 2π × 20 kHz and f = 0,
thereby matching the decoherence rate γ₀ studied in Fig. 3 (as
was similarly found for the steering regions in terms of C±
above [left column of Fig. 2]).

Next, in Figs. 3(b) and 3(d), we show the bare vari-
ces (ΔX±)² and the steerabilities E±± and E±|+ as func-
tions of the interaction angle θ± while fixing θ− = 0.35π.
Since higher degree of the sideband asymmetry (larger
θ±) corresponds to better dynamical cooling for fixed C±
[Eqs. (4)], (ΔX±)² is decreased with increasing θ± as shown
in Figs. 3(b) and 3(d). Meanwhile, due to the combined effects
of the different degrees of the dynamical cooling and the
induced asymmetric noise interference shown in Eqs. (8),
the behavior of E±± and E±|+ with increasing θ± is generally
not monotonic. Optimal choices of θ± for maximizing the
steerabilities exist in the region of f < 0, which we will
explore in the next section.

V. STEADY-STATE STEERING OPTIMIZATION

Since EPR steering plays a key role in the implementa-
tion of 1sDI quantum tasks, in this section we apply and optimize
our scheme as a steering resource for such applications.
The particular scenario we will consider is that in which an
untrusted client node wants to connect to a trusted server node,
hence requiring steering from the former to the latter system
in order to enable 1sDI tasks. In order to restrict the parameter
space of our optimization, we will make assumptions about
the accessible range of parameters for the two subsystems. To
this end, we imagine a quantum network in which a number of
relatively cheap client nodes are connected to a relatively
expensive central server node. It seems reasonable to
assume that a “cheap” client node has limited ranges of interaction
strength and type with the optical field (parametrized by C and θ),
as compared to the “expensive” server node, and we
therefore take these client parameters to be the constrained
parameters in the steering optimization below (while assum-
ing the server parameters to be freely tunable). Under
these circumstances, we find that the optimal cascade ordering is to
let the client be the first subsystem and the server the second
subsystem, corresponding to labels (−) and (+), respectively,
in preceding sections; henceforth, we focus on this case.
While the steering from client to server node is the quantity
of primary interest in the present section, as motivated above,
we will for comparison also optimize and plot the steering in
the opposite direction.

Given the above considerations, we proceed by separately
optimizing the steerability in each direction, E±± and E±|+, for a
given value of the client cooperativity, C−, i.e., evaluating
the remaining parameters C± and θ± at their optimal values
(these optimal parameter values are plotted in Appendix A).
The resulting minimal values of E±±|± are shown in Fig. 4 (a)
showing that the unidirectional coupling of the first (−) to

\[ \text{FIG. 4. } \text{E}±±|± \text{ (dashed) and E}±|+ \text{ (solid) as a function of } C− \text{ with optimal interaction types } \theta± \text{ and quantum cooperativity } C± \text{ when } f = 0 \text{ and } f ≠ 0, \text{ in the cases (a) } ε = 0 \text{ and (b) } ε = 0.2, \text{ i.e., without and with transmission losses. The two sets of thermal parameters are (thick blue curves) intrinsic linewidth } γ±,0 = 2π × 0.1 \text{ Hz, thermal occupation number } n±,0 = 10^5; \text{ (thin orange curves) } \gamma±,0 = 2π × 0.1 \text{ Hz, } n−,0 = 2π × 0.1 \text{ Hz, } n+,0 = 10^5, \text{ and } n±,0 = 0. \]

the second (+) subsystem induced by asymmetric coupling

types f ≠ 0 (presented by the blue and orange curves) can sig-
ificantly enhance the steerability in both directions (indicated
by the smaller values of E±± and E±|+), as compared with
the case of symmetric coupling, f = 0 (i.e., forcing θ± = 0,
presented by the red and black curves). The corresponding
optimal asymmetric interaction angles (resulting in the blue
and orange curves) show that in the regime where n± ≫ 1,
the optimal interaction type between the first subsystem (−)
and the light field is QND interaction (θ± ≈ π/4) for all
C− ≥ 1; this corresponds to no sideband asymmetry (Γ−|B =
Γ−|P), a condition which will typically be easy to fulfill and
hence is compatible with our assumption of the “cheap”
client system having limited tunability of its interaction type,
θ− (this is true for, e.g., unresolved-sideband optomechani-
systems and free-space spin ensembles). Meanwhile, for
the second subsystem (+), more cooling (beam-splitter-type)
than heating (parametric-down-conversion-type), i.e., θ+ >
π/4 ⇒ Γ−|B > Γ−|P, is required. Taken together, these opti-
mal values for θ± indicate that choosing f < 0 is beneficial
for maximizing the steerabilities in our hybrid system.
This result is consistent with that presented in Ref. [53], i.e., the
additional interference effect allowed by the optimal interaction
angles can be used to achieve the maximum noise cancellation
in the EPR variables and thus enhance the correlation between
the two subsystems.

Having established the advantage of the unidirectional
coupling corresponding to f < 0, we now turn to the asym-
bmetry between the optimal steering achievable in the two
directions. As seen in Fig. 4, we find the optimal client-
to-server steerability E±±|± to significantly outperform the
opposite direction E±|+, for moderate client cooperativities
C− ≤ 10 in the absence of transmission losses [Fig. 4(a) and
for all C− in the presence of moderate losses [Fig. 4(b)]; the
situation is qualitatively the same whether the server system’s
thermal bath is assumed to be hot (blue curves) or vacuum
(oranges curves), while keeping the decoherence rate γ±,0
fixed, although the latter scenario is seen to be preferable.
It follows from these results that our scheme is especially
advantageous in the technological scenario envisaged here,
i.e., producing the steering required for 1sDI quantum com-
communications between a poorly tunable untrusted client node
and a highly tunable trusted server node.
Considering the effect of transmission losses $\epsilon > 0$ [Fig. 4(b)], the optimal steerabilities are degraded, but to different degrees in the two directions for $f \neq 0$, even in the limit of large $C_-$. This is to be expected from Eqs. (8), where $\epsilon$ enters asymmetrically in $E_{+|-}$ and $E_{-|+}$, and hence will affect the optimal steering in the two directions differently when $f \neq 0$. To be specific, besides the reduction of the covariance term $[\langle \hat{X}_- \rangle, \langle \hat{X}_- \rangle^\dagger]$, nonzero $\epsilon$ will also affect the additional noise interference, and thus change $(\Delta \hat{X}_-)^2$, while it has no influence on $(\Delta \hat{X}_+)^2$. In Fig. 4(b), this asymmetry of nonzero $\epsilon$ is seen to increase the separation $E_{+|-} < E_{-|+}$ between the optimal steerabilities. In fact, considering the transmission loss $\epsilon$ as an effective external loss added to the second (+) oscillator, this result is consistent with that of earlier papers [7,9,61], i.e., the decoherence of EPR steering is substantial when the loss is on the steering object but much less sensitive to the loss on the steered object. The loss is added to the second (+) oscillator which acts as the steering object in $E_{-|+}$, but as the steered party in $E_{+|-}$, such that the loss reduces the correlation in the direction $+ \Rightarrow -$ more than the other direction, i.e., the value of $E_{-|+}$ is higher than $E_{+|-}$. This asymmetric effect of loss with respect to the two subsystems is another consequence of the inherently asymmetric nature of EPR steering, which does not apply to entanglement.

Since transmission losses are a crucial factor in any quantum network architecture, in Fig. 5 we study further the robustness of our scheme in this regard, focusing on the optimized client-to-server steerability $E_{+|-}$. The tolerance to transmission losses $\epsilon$ is seen to depend on both the client cooperativity $C_-$ and the thermal parameters of the server, i.e., the intrinsic linewidth $\gamma_{-0}$ and the thermal occupation $\bar{n}_-$. In the case of large cooperativity, $C_- = 100$, $E_{+|-}$ is almost equal for the two sets of thermal parameters considered in Fig. 5. However, when $C_-$ is small or moderate, the case that assumes vacuum-state thermal parameters for the server (+) subsystem (orange curves) can tolerate more loss than the case of hot thermal parameters (blue curves) while achieving the same $E_{+|-}$. The maximum loss tolerance for the case of the hot thermal parameters for the server (+) subsystem is $\epsilon < 0.9$ when $C_- = 10$ and $\epsilon < 0.5$ when $C_- = 2$. Note that $E_{+|-} < 0.5$ can be achieved for arbitrary $\epsilon < 1$ when assuming vacuum-state thermal parameters for the server (+) subsystem.

VI. OPTIMALITY AND IMPLEMENTATION

As a final but essential part of our analysis, we address the question of optimality for our unconditional scheme. In this regard, a natural question is whether our scheme wastes information by discarding the propagating light field after it has interacting with both subsystems (Fig. 1). To investigate this, we have recalculated the optimal steerabilities (considered in Fig. 4) that can be achieved when additionally measuring the joint output light field and optimally combining this measurement record with the verification measurements of the individual subsystems. Mathematically, this is achieved by solving the corresponding stochastic master equation, yielding covariance matrix elements generalizing Eqs. (4) to incorporate the information gained from the joint output field. The details of this procedure for the hybrid system under consideration here are given in the Supplementary Material of Ref. [53] and hence will not be reproduced here. Evaluating this conditional scheme and optimizing the performance under the same constraints as in Fig. 4 (in particular, demanding dynamical stability), we find that the improvement in the steerabilities due to the added measurement of the joint output field is negligible compared to our unconditional scheme (plots are presented in Appendix B); this is similar to what has been found for entanglement generation in this hybrid system [53]. One can interpret this outcome as being due to the second subsystem in the cascade acting as a coherent measurement device, rendering additional measurements on the joint field superfluous. This establishes the advantage of our scheme that the optimal steerabilities can be obtained unconditionally (however, further improvements are likely possible by adding active feedback stabilization [47]).

Having completed the analysis of our generic scheme, we now mention a couple of candidate physical systems for implementing it: collective spin ensembles and mechanical systems. For both kinds of systems, the interaction strength and type with the light field (i.e., $\Gamma$ and $\theta$) can be efficiently manipulated by embedding them in a suitable optical cavity [56,62,63]. Current state-of-the-art optomechanical experiments have demonstrated $C \gtrsim 30$ [64], although in the unresolved-sideband regime. If an optomechanical system is used to implement the second system in the cascade (Fig. 1), then, generally, a rather sideband-resolved cavity is required in order to attain the optimal performance discussed in Sec. V. Note that in the context of optomechanics, the quantum cooperativity $C \propto \langle g_0 / k \rangle^2 |\alpha|^2 / \gamma_{M0}$, where $g_0$ is the single-photon coupling rate and $\kappa$ is the cavity decay rate. Hence, large values $C > 1$ can be achieved by increasing the intracavity drive field $\alpha$ or decreasing the mechanical intrinsic dissipation $\gamma_{M0}$ while keeping the ratio $g_0 / k < 1$, so that the system remains in the linearized optomechanical regime [56]. Concerning spin ensembles, cooperativities $C \gtrsim 1$ are feasible [50,52] and larger values are achievable by means of cavity enhancement [62,63]. However, such enhancement typically comes at the cost of increased optical losses (effectively larger $\epsilon$), prompting an experimental trade-off between large $C$ and small $\epsilon$.  

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The candidate systems discussed here have inspired the choices of thermal parameter sets used in the plots above, as we will now describe. The effective thermal occupation of a collective spin oscillator is due to imperfect optical pumping, which is typically equivalent to a near-vacuum bath, $\bar{n} \lesssim 1$. Additionally, the power broadening induced by the spontaneous emission can result in large intrinsic linewidths of such spin oscillators [32], $\gamma_0/(2\pi) \gtrsim 1$ kHz. For the mechanical oscillators, the thermal occupation is determined by the environment temperature and the resonance frequency, leading in most instances to $\bar{n} \gg 1$. However, small intrinsic damping rates corresponding to quality factors $Q > 10^6$ are routinely achieved [56] and the state of the art is $Q \gtrsim 10^9$ [64]. For mechanical oscillators with $\Omega/(2\pi) \sim 1$ MHz, this amounts to intrinsic linewidths in the range $\gamma_0/(2\pi) \sim 1$ mHz–1 Hz.

VII. CONCLUSION

In conclusion, we have analyzed how to unconditionally generate tunable symmetric and asymmetric steady-state EPR steering in macroscopic hybrid systems composed of two thermal oscillators with masses of opposite signs coupled to a unidirectional light field. We have developed an approach to controlling the asymmetry of EPR steering by tuning the directional coupling of the first to the second subsystem resulting from the asymmetric interaction types between the subsystems and the light field. Instead of the methods of adding extra asymmetric amounts of noises or losses to each subsystem, our scheme provides an active method for the control of asymmetry of steering within the apparatus itself. Investigating possible applications, we find that our scheme can be used to engineer enhanced steering from an untrusted node of limited tunability to a trusted, highly tunable node, thus allowing for 1sDI quantum information tasks in macroscopic hybrid quantum networks.

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APPENDIX A: OPTIMAL PARAMETERS FOR EPR STEERING IN A PARTICULAR DIRECTION

In this section, we present the details of the numerical minimization of $E_{±1}$ and $E_{±\perp}$, as shown in Fig. 4 in the main text. In particular, we plot the optimal values of the interaction angles $\theta_{±}$ and the cooperativity ratio $C_+ / C_-$ required to realize the minimal $E_{±\perp}$.

As illustrated in Fig. 6, the optimal asymmetric interaction shows $\theta_\perp = \pi / 4$ when minimizing $E_{+-}$ and $E_{-\perp}$ below 1/2. The optimal $\pi / 4 < \theta_- \leq \pi / 2$ indicates that more beam-splitter interaction (cooling) than parameter-downconversion interaction (heating) is required for the second (+) subsystem. The optimal asymmetric interaction corresponds to $f < 0$, which is consistent with our analysis in the main text. In the case of the symmetric coupling ($\theta_\perp = 0$), i.e., $f = 0$, $\pi / 4 < \theta < \theta_\perp$ indicates that to generate EPR steering, less cooling for the second (+) subsystem is required, but the first (−) subsystem should also implement the same degree of the dynamical cooling.

The effect of the optical transmission losses ($\epsilon$) on optimizing the interaction angles can be seen by comparing Figs. 6(a) and 6(b), and also Figs. 6(c) and 6(d). It shows that the optimal interaction of the first (−) subsystem is still $\theta_- = \pi / 4$, but more beam-splitter interaction is required for the second (+) subsystem in the presence of the transmission loss $\epsilon \neq 0$. Moreover, the optimal choices of $\theta_\perp$ for minimizing $E_{1\perp}$ and $E_{-\perp}$ differ even in the limit of large cooperativities $C_{±\perp}$, which is different with the case of the symmetric coupling when $\epsilon = 0$.

Now we come to the results of the optimal ratio of the quantum cooperativities $C_+ / C_-$ for the minimized $E_{1\perp}$ and $E_{-\perp}$. As shown in Fig. 7, the optimal $C_+ / C_-$ to minimize the steering parameters when allowing asymmetric coupling are larger than 1, while in the case of the symmetric coupling, the optimal $C_+ / C_- < 1$ occurs when minimizing $E_{-\perp}$ for the fixed asymmetric thermal parameters (black dashed curve).

In the limit of the large cooperativity $C_-$, the optimal $C_+ / C_-$ for the two minimized steerabilities ($E_{1\perp}$) both approach 1 both for the cases of symmetric and asymmetric coupling, in the absence of optical transmission loss $\epsilon$ = 1/2.
FIG. 7. The optimal ratio of quantum cooperativities ($C_+/C_-$) for the minimized $E_{+|+}$ (dashed) and $E_{-|+}$ (solid) as a function of $C_-$ for the fixed thermal parameters as intrinsic linewidth $\gamma_{\pm,0} = 2\pi \times 0.1$ Hz and thermal occupation number $\bar{n}_\pm = 10^5$ when $f = 0$ (red thin curves) and $f \neq 0$ (blue thick curves), as shown in panels (a) and (b). Panels (c) and (d) represent the scenario of asymmetric thermal parameters with intrinsic linewidths $\gamma_{+,0} = 2\pi \times 0.1$ Hz, $\gamma_{-,0} = 2\pi \times 20$ kHz and thermal occupation numbers $\bar{n}_- = 10^5$, $\bar{n}_+ = 0$, when $f = 0$ (thin black curves) and $f \neq 0$ (thick orange curves).

0. However, in the presence of $\epsilon$, the optimal $C_+/C_-$ that minimize $E_{+|+}$ and $E_{-|+}$ remain different when choosing the asymmetric coupling.

Note that in Fig. 7 the optimal ratio $C_+/C_-$ for the symmetric coupling to minimize $E_{+|+}$ (red solid and black solid curves) is plotted in the regime of $\theta < \pi/2$ (Fig. 6). The reason is when the optimal interaction angle is $\theta = \pi/2$, $E_{+|+} = (\Delta \tilde{X}_-)^2$ is independent of the value of $C_+$, as can be seen from Eqs. (4) and (8) in the main text. Moreover, when considering the asymmetric thermal parameters, the optimal ratio $C_+/C_-$ for the symmetric coupling to minimize $E_{+|+}$ [black dashed curve in Figs. 7(c) and 7(d)] is plotted in the range where the corresponding optimal interaction angle $\theta < \pi/2$. This can be understood similarly from Eqs. (4) and (8) in the main text, where $E_{+|+} = (\Delta \tilde{X}_-)^2 = (\Gamma_+ + \gamma_{+,0})/(\gamma_{+,0} + \Gamma_+)$ when $\theta = \pi/2$. For $\bar{n}_+ = 0$, $E_{+|+} = 1/2$ becomes irrelevant with the value of $C_+$ and also $\gamma_{+,0}$.

FIG. 8. The relative improvement $d$ of the optimal $E_{+|+}$ (dashed) and $E_{-|+}$ (solid) as a function of $C_-$ for the fixed thermal parameters as intrinsic linewidth $\gamma_{\pm,0} = 2\pi \times 0.1$ Hz and thermal occupation number $\bar{n}_\pm = 10^5$ (thick blue curves). The thin orange curves are plotted based on the asymmetric thermal parameters: intrinsic linewidths $\gamma_{+,0} = 2\pi \times 0.1$ Hz, $\gamma_{-,0} = 2\pi \times 20$ kHz and thermal occupation numbers $\bar{n}_- = 10^5$, $\bar{n}_+ = 0$.

APPENDIX B: COMPARISON BETWEEN UNCONDITIONAL AND CONDITIONAL SCHEMES

We use the relative improvement of the minimized steering parameters ($E_{+|+}$, $E_{-|+}$) of the conditional scheme over the unconditional scheme to compare the performances of the two schemes in the dynamically stable regime, i.e., $\gamma_+ > 0$. The relative improvement is defined as $d = (E_u - E_c)/E_u$, where $E_{\text{abc}}$ is the minimal degree of the steering parameters that can be achieved by optimizing the relevant parameters in the unconditional and conditional schemes.

As shown in Fig. 8, the relative improvement of the optimized steerabilities ($E_{+|+}$, $E_{-|+}$) by adding the measurement of the joint output light field is small for the cases of typical interest. In particular, for the client-to-server steerability $E_{+|+}$, $d < 1\%$ within the entire range of interest for $C_-$. We hence conclude for the generation of EPR steering that our unconditional scheme can achieve practically the same optimal performance as that of the conditional scheme under the conditions considered in Fig. 4 in the main text.


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