I. INTRODUCTION

The quantum nature of correlation goes beyond quantum entanglement. There are separable states that contain correlation with no classical counterpart. Researches show that such separable states can also be useful for quantum computation [1], quantum state discrimination [2] and quantum communication [3–5]. The importance of quantum correlation also lies in its close connection to quantum entanglement [6–8]. Various ways for detecting and measuring the quantum correlation have been proposed [9–13] and the dynamics of quantum correlation under noises are also studied, see for example [14]. Among the different measures for quantum correlation, the quantum discord and one-way quantum deficit receives their physical interpretations [15–17].

Counterintuitively, local operation can create quantum correlation in some classically correlated states [18–22]. In particular, any separable state with positive quantum discord can be produced by local positive-operator-valued measure (POVM) on a classical state in a larger Hilbert space [23]. The criteria for checking whether a local trace-preserving operation is able to generate quantum correlation has recently been obtained. For a single-qubit channel, it can create quantum correlation in some classical states if and only if it is neither a unital channel nor a classical channel [18]. For a quantum channel of arbitrary finite dimension, it is able to create quantum correlation if and only if it is not a commutativity-preserving channel [19, 20].

On solving the problem whether a local channel can create quantum discord, it is natural to ask the following question: how much quantum correlation can be built by local operation? In this article, we investigate the problem by defining quantum-correlating power of a local quantum channel, which quantifies the maximum quantum correlation that can be generated by the channel. For any local channels, the input state which corresponds to the maximum quantum correlation in the output state is proved to be a classical-classical state. Further, the quantum state with maximum quantum correlation which is obtained local operation on a two-qubit classical-quantum state can be found in the class of rank-2 quantum-classical states. The analytic expression for QCP of single-qubit amplitude damping channel is calculated as an example. The interesting effect that two zero-QCP channels can consist a positive-QCP channel is observed, and is named as the super-activation of QCP. As a by-product, we find a class of states with zero pair-wise correlation but non-zero genuine quantum correlation.

II. QUANTUM-CORRELATING POWER AND OPTIMAL INPUT STATE

Generally, a state is said to have zero quantum correlation on A if and only if there is a measurement on A that does not affect the total state. Such states are called classical-quantum states. We label $C_0$ as the set of all classical-quantum states. Then $C_0$ can be written as

$$C_0 = \{\rho | \rho = \sum_i q_i \Pi^A_{i} \otimes \rho^B_i \},$$

where $\{\Pi^A_{i} = |\alpha_i\rangle\langle\alpha_i|\}$ are a set of orthogonal basis of part A.

Various measures for quantifying quantum correlation have been proposed. For example, quantum discord [9] is defined as the minimum part of the mutual information shared between A and B that cannot be obtained by the measurement on A

$$\delta_{B|A}(\rho) = \min_{\{F^A_i\}} S_{B|A}(\rho F^A_B) - S_{B|A}(\rho),$$

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where $S_{A|B}(\rho) = S(\rho) - S(\rho_B)$ with $S(\rho) = -\text{Tr}(\rho \log_2 \rho)$ is conditional entropy, $\{F_A^i\}$ is a POVM on qudit $A$, and $\rho_{F_A^iB} = \sum_i F_A^i \rho F_A^{i\dagger}$ is the state of qudits $A$ and $B$ after the POVM. It has been proved that, for separable states, the optimal POVM is just von Neumann measurement $\{\Pi_A^i\}$ [24]. Another example is the distance-based measure of quantum correlation [18]

$$Q_D(\rho) = \min_{\sigma \in C_0} D(\rho, \sigma),$$

(3)

where the state distance satisfies the property that $D$ does not increase under any quantum operation. Trace-norm distance $D_1 = \text{Tr}|\rho - \sigma|/2$ with $|O| = \sqrt{O^\dagger O}$ and relative entropy $S(\rho || \sigma) = \text{Tr}[\rho (\log_2 \rho - \log_2 \sigma)]$ are examples satisfying this property [22]. One-way quantum deficit

$$\Delta_{B|A} = \min_{\{A_i\}} S(\rho_{\Pi_A^iB}) - S(\rho),$$

(4)

is in fact the minimum relative entropy to classical-quantum states [22] and thus belongs to this class of quantum correlation measure. Notice that the measures of quantum correlation are asymmetric for $A$ and $B$. Here and after, we only discuss the quantum correlation defined on $A$.

The measure of quantum correlation $Q$ we discuss in this article satisfy the following three conditions. (a) $Q(\rho) = 0$ iff $\rho \in C_0$; (b) $Q(U\rho U^\dagger) = Q(\rho)$ where $U$ is a local unitary operator on $A$ or $B$; (c) $Q(I \otimes B(\rho)) \leq Q(\rho)$. Conditions (a) and (b) are satisfied by most of the quantum correlation measures. It has been proved that quantum discord satisfies condition (c) [28]. Here we briefly prove that $Q_D$ satisfies condition (c). Suppose the closest classical-quantum state to $\rho$ is labeled as $\sigma$, then we have $Q_D(\rho) = D(\rho, \sigma) \geq D(\Lambda_B(\rho), \Lambda_B(\sigma)) \geq Q_D(\Lambda_B(\rho))$. The last inequality holds because $\Lambda_B(\sigma)$ is still a quantum-classical state, but may not be the closest one to $\Lambda_B(\rho)$. It should be noticed that geometric quantum discord does not satisfy condition (c) [29], and is thus out of the scope of this paper.

Local operations on $A$ can create quantum correlation from a classical-quantum state. In order to characterize how much quantum correlation can be created by a local channel, we introduce the definition of quantum-correlating power.

**Definition (quantum-correlating power).** The quantum-correlating power of a quantum channel is defined as

$$Q(\Lambda) = \max_{\rho \in C_0} Q(\Lambda \otimes I(\rho)),\tag{5}$$

where $Q$ is a measure of quantum correlation which satisfies conditions (a-c).

The input state $\rho$ that corresponds to the maximization in Eq. (5) is called the optimal input state. Here we give a general form of the optimal input state.

**Theorem 1.** For any $d$-dimension local channel acting on $A$, the optimal input state with the maximum amount of quantum correlation in the output state is a classical-classical state of form

$$\rho = \sum_{j=0}^{d-1} q_j \Pi_B^{j\beta_j} \otimes \Pi_{\beta_j},\tag{6}$$

where $\{\Pi_B^{j\beta_j} = |\beta_j\rangle \langle \beta_j|\}$ is the orthogonal basis for the Hilbert space of qudit $B$.

**Proof.** Consider a classical-quantum state $\rho' \in C_0$ as input state. After a local channel on $A$, the state becomes

$$\rho' = \sum_i q_i \Lambda(\Pi_A^i) \otimes \rho_i^B.$$

(7)

For input state $\rho$ as in Eq. (6), the corresponding output state is

$$\rho = \sum_i q_i \Lambda(\Pi_A^i) \otimes \rho_i^B.$$  

(8)

We first prove that $\rho'$ can be prepared from $\rho$ by a local operation on $B$. Writing the $d$ states of qudit $B$ in Eq. (7) as $\rho_k^B = \sum_{i=0}^{d-1} \lambda_i^{(k)} |\phi_i^{(k)}\rangle \langle \phi_i^{(k)}|$, $k = 1, \ldots, d$, we find a rank-1 channel $\Lambda_B(\cdot) = \sum_{k=1}^{d} \sum_{i=0}^{d-1} \lambda_i^{(k)} E_i^{(k)} \cdot E_i^{(k)*}$, where $E_i^{(k)} = |\phi_i^{(k)}\rangle \langle \beta_k|$, such that $\Lambda_B(\Pi_{B\beta_j}) = \rho_k^B$. It means that $\rho = I \otimes \Lambda_B(\rho')$. Reminding that local operation on $B$ never increase the quantum correlation on $A$, we have $Q(\rho) \geq Q(\rho')$. It means that for any state $\rho'$ in the form of Eq. (7), we can always find a state $\rho$ in the form of Eq. (5), whose quantum correlation is larger than $\rho'$. Therefore, state in form of Eq. (6) is the optimal input state. This completes the proof of Theorem 1.

## III. Channels with Maximum QCP

We have investigated the maximum quantum correlation that can be created by a given local channel. It is also interesting to ask the following question: how much quantum correlation can be generated from a classical state when all the local quantum operation is allowed? In this section, we focus on finding the single-qubit channels with maximum QCP.

**Lemma 1.** For any two states of a qubit $\rho_j$, $j = 0, 1$, there exist two pure states $|\psi\rangle$ and $|\phi\rangle$, such that $\rho_j = p_j |\phi\rangle \langle \phi| + (1 - p_j) |\psi\rangle \langle \psi|$, where $0 \leq p_j \leq 1$, $j = 1, 2$.

**Proof.** We will first prove that for any two states of a qubit $\rho_1$ and $\rho_2$, there exist a pure state $|\psi\rangle$, such that

$$\rho_1 = p_\psi + (1 - p_\psi) |\psi\rangle \langle \psi|,\quad 0 \leq p_\psi \leq 1.$$

(9)

We discuss this problem in the Bloch presentation: $\rho_j = (I + c_j \cdot \vec{\sigma})/2$, $j = 1, 2$, and $|\psi\rangle = (I + \vec{\sigma} \cdot \vec{a}) |\psi\rangle$, where $\vec{\sigma} = \{\sigma_x, \sigma_y, \sigma_z\}$ are Pauli matrices, $c_j = \text{Tr}(\rho_j \vec{\sigma})$ and $\vec{a} = \langle \psi | \vec{\sigma} | \psi \rangle$. Then Eq. (9) is equivalent to

$$c_1 = p c_2 + (1 - p) \vec{a},\tag{10}$$

where $|c_j| \leq 1$ and $0 \leq p \leq 1$. $|\vec{a}| = 1$ leads to $p = \frac{1 - c_1 \cdot c_2 - (1 - c_1 \cdot c_2)^2 - (1 - |c_1|^2)(1 - |c_2|^2)/(1 - |c_2|^2)}{1 - |c_2|^2}$. It
is straightforward to verify that $0 \leq p \leq 1$. Therefore, Eq. (10) holds.

Consequently, for $\rho_2$ and $|\psi\rangle$, we can always find a pure state $|\phi\rangle$ such that

$$
\rho_2 = p'|\psi\rangle\langle\psi| + (1-p')|\phi\rangle\langle\phi|, \quad 0 \leq p' \leq 1.
$$

Combining Eqs. (9) and (11), we have $\rho_1 = (1-p + pp')|\psi\rangle\langle\psi| + p(1-p')|\phi\rangle\langle\phi|$. This completes the proof of Lemma 1. It is worth mentioning that $\delta^0$ and $\delta^1 = \langle \phi | \sigma | \phi \rangle$ are just the two intersections of the Bloch sphere surface and the line $\overline{c_0c_1}$, where $\overline{c_0c_1}$ is the line fixed by the two points $c_0$ and $c_1$.

Now we are ready to prove the second central result of this paper.

**Theorem 2.** The local single-qubit channel with maximum QCP can be found in the set of channels

$$
\mathcal{D}_0 = \{ \Lambda | \Lambda(\cdot) = \sum_{i=0}^{1} E_i(\cdot) \hat{E}_i, \hat{E}_i = |\psi_i\rangle\langle\alpha_i| \},
$$

where $|\psi_0\rangle$ and $|\psi_1\rangle$ are two non-orthogonal pure states.

**Proof.** In order to find out the maximum-QCP channel, we investigate the form of optimal output state, which contains the maximum quantum correlation created by local operations on a classical-classical state. The optimal output state can be found in the subset of the rank-2 quantum-classical state

$$
\tilde{C}_0 \equiv \{ \tilde{\rho} \tilde{\rho} = \sum_{i=0}^{1} p_i |\psi_i\rangle\langle\psi_i| \}.
$$

The reason is as follows. Consider the optimal input state as in Eq. (6) and the corresponding output state as in Eq. (8) with $d = 2$. According to lemma 1, each $\rho_j \equiv \Lambda | E_j \rangle \langle \Lambda|$ can be decomposed as $\rho_j = \sum_{i=0}^{d-1} \rho_{i}^{(j)} |\psi_{i}\rangle\langle\psi_{i}|$, $j = 0, 1$, and consequently, Eq. (8) can be written as

$$
\rho = \sum_{i=0}^{1} p_i |\phi_{i}\rangle\langle\phi_{i}| \otimes \xi_i,
$$

where $p_i = \sum_{j=0}^{d-1} q_{j} p_{i}^{(j)}$ and $\xi_i = (\sum_{j=0}^{d-1} q_{j} p_{i}^{(j)} \langle j | j \rangle) / p_{i}$ for $i = 0, 1$. From the proof of theorem 1, any state $\rho$ in form of Eq. (13) can be obtained from $\tilde{\rho}$ in Eq. (13) by some local operations on $B$. Meanwhile, the quantum correlation we discuss here can not be increased by local operation on $B$. Therefore, the optimal output state which contains the maximum correlation can be found in $\tilde{C}_0$. Further, for any output state $\tilde{\rho} \in \tilde{C}_0$, we can find a channel $\Lambda \in \mathcal{D}_0$ which takes a classical input state to $\tilde{\rho}$. This completes the proof of theorem 2.

Based on theorem 2, we derive the local single-qubit channel with the maximum QCP based on quantum discord. We first need to find $\tilde{\rho} = p_0 |00\rangle\langle00| + p_1 |\phi\rangle \langle\phi| \in \tilde{C}_0$ which contains the maximum quantum discord. The quantum discord of a rank-2 two-qubit state can be calculated analytically using the Koashi-Winter relation

$$
\delta_{B|A} = \mathcal{E}_{BC} + S_{B|C},
$$

where $\mathcal{E}_{BC}$ is the entanglement of formation (EOF) between qubits $B$ and $C$, and qubit $C$ is the purification of state $\tilde{\rho}$

$$
|\Psi\rangle_{ABC} = \sqrt{p_0} |000\rangle + \sqrt{p_1} |111\rangle.
$$

Therefore, we have

$$
\delta_{B|A}(\tilde{\rho}) = h(\sqrt{1-t^2} \sin \phi) + h(\sqrt{1-(1-t^2) \sin^2 \phi}) - h(t),
$$

where $t = p_0 - p_1$. Eq. (17) reaches its maximum $\delta_{max} \approx 0.2017$ at $\phi = \pi/4$ and $t = 0$. Therefore, the channels with maximum QCP should satisfy $\Lambda_{max}(|\phi\rangle\langle\phi|) = |\phi\rangle\langle\phi|$ and $\Lambda_{max}(|\phi + \pi/2\rangle\langle\phi + \pi/2|) = |\phi + 3\pi/4\rangle\langle\phi + 3\pi/4|$. It is direct forward to write a class of maximum-QCP channels, which are unitarily equivalent to $\Lambda(\cdot) = \sum_{i=0}^{1} \hat{E}_i(\cdot) \hat{E}_i^\dagger$, where

$$
\hat{E}_0 = |0\rangle\langle0|, \hat{E}_1 = |+\rangle\langle1|,
$$

and the corresponding QCP is

$$
Q_\Lambda(\Lambda_{max}) = 2h\left(\frac{1}{\sqrt{2}}\right) - 1 \approx 0.2017.
$$

It is worth mentioning that there are several separable states containing larger quantum discord. For example, for separable state $\rho = (|\Phi^+\rangle\langle\Phi^+| + |\Psi^+\rangle\langle\Psi^+|) / 2$ with $|\Phi^+\rangle = (|00\rangle + |11\rangle) / \sqrt{2}$ and $|\Psi^+\rangle = (|01\rangle + |10\rangle) / \sqrt{2}$ two Bell states, the quantum discord is $\delta(\rho) = 3/4$, according to the result of Ref. [29]. Such states can not be prepared by local operations from a classical state.

**IV. QCP OF AMPLITUDE DAMPING CHANNEL**

In this section, we will show exactly how to calculate the QCP by providing an example. The amplitude damping (AD) channel $\Lambda^{AD}$ describes the evolution of a quantum system interacting with a zero-temperature bath. The operator-sum presentation of AD channel is

$$
\Lambda^{AD} = \sum_{i=0}^{1} E_i(\cdot) E_i^\dagger,
$$

where $E_0^{AD} = |0\rangle\langle0| + \sqrt{p} |1\rangle\langle1|$ and $E_1^{AD} = \sqrt{1-p} |0\rangle\langle1|$. Here we choose quantum discord and one-way quantum deficit as measure of quantum correlation in Eq. (3). Now we are ready to calculate the QCP of AD channel.

According to theorem 1, the optimal input state should be of form

$$
\rho = q_1 |\theta\rangle \langle\theta| \otimes |0\rangle\langle0| + q_2 |\theta + \pi/2\rangle \langle\theta + \pi/2| \otimes |1\rangle\langle1|,
$$

where $|\theta\rangle = \cos \theta |0\rangle + \sin \theta |1\rangle$. Intuitively, $q_1 = q_2 = 1/2$ should be chosen to maximize the initial classical correlation, while $\theta = \pi/4$ should hold such that the coherence between the two energy levels $|0\rangle$ and $|1\rangle$ of qubit $A$ is maximized. These are verified by numerical results.
Depending on the above discussion, the analytical expression of QCP defined on quantum discord and one-way quantum deficit are respectively
\[
Q_{\Delta}(A^{\text{AD}}) = h(p) + h(\sqrt{1-p}) - h(\sqrt{1-p + p^2}) - 1, \tag{21}
\]
and
\[
Q_{\Delta}(A^{\text{AD}}) = \min\{h(\sqrt{1-p}) - h(1 - p + p^2), \\
\quad h(p) - h(1 - p + p^2), \\
\quad \frac{h(t_1) + h(t_2)}{2} - h(\sqrt{1-p + p^2})\}, \tag{22}
\]
where \(h(x) = -\frac{1}{2} x \log_2 \frac{1+x}{2} - \frac{1-x}{2} \log_2 \frac{1-x}{2}, \)
\(t_1 = \sqrt{1-p} \sin 2\chi + p \cos 2\chi, \)
\(t_2 = \sqrt{1-p} \sin 2\chi - p \cos 2\chi, \)
where \(\chi\) satisfies
\[
\tan 2\chi = \frac{\sqrt{1-p} \log_2 \left(\frac{(1+p \sin 2\chi)^2 - (p \cos 2\chi)^2}{(1-\sqrt{1-p} \sin 2\chi)^2 - (1-p \cos 2\chi)^2}\right)}{\log_2 \left(\frac{(1+p \cos 2\chi)^2 - (p \sin 2\chi)^2}{(1-\sqrt{1-p} \cos 2\chi)^2 - (1-p \sin 2\chi)^2}\right)}. \tag{23}
\]

The optimal measurement basis \(\{|\chi\}, |\chi + \pi/2\}\) in the definition of one-way quantum deficit as in Eq. (21) transfers gradually from \(|\{\pm\}, \{-\}\}\) to \(|\{0\}, |1\}\), as shown in Fig. 2 while for quantum discord, the optimal measurement is always \(|\{\pm\}, |\{-\}\}\).

V. SUPER-ACTIVATION OF QCP

In this section, we will claim an interesting property of QCP. Consider two classical-quantum states \(\rho_{AB}^{\prime}\) and \(\rho_{A'B'}^{\prime}\) with qubits \(A\) and \(A'\) at one site and qubits \(B\) and \(B'\) at another. A local two-qubit unitary operator acting on qubits \(A\) and \(A'\) can activate two zero-QCP single-qubit channels into a positive QCP two-qubit channel. We call this phenomenon the super-activation of QCP.

We here give an example of phase-damping (PD) channel to show exactly how this property works. The Kraus operators of PD channel are \(E_0^{\text{PD}} = |0\rangle\langle 0| + \sqrt{1-p}|1\rangle\langle 1|\)
\(E_1^{\text{PD}} = \sqrt{p}|1\rangle\langle 1|\). Clearly, PD channel is a mixing channel, which means that quantum correlation cannot be created when a single copy of classical-quantum state is considered.

Now consider initial state of qubits \(A\) and \(B\)
\[
\rho_{AB}^{\prime} = \frac{1}{2} \sum_{i=0}^{1} |i\rangle_A \langle i| \otimes |i\rangle_B \langle i|. \tag{24}
\]
Qubits \(A'\) and \(B'\) are in the same state, then the total state of the four qubits is
\[
\rho = \frac{1}{4} \rho_{AB}^{\prime} \otimes \rho_{A'B'}^{\prime} = \frac{1}{4} \sum_{i,j} |ij\rangle_{AA'} \langle ij| \otimes |ij\rangle_{BB'} \langle ij|. \tag{25}
\]
Now apply a two-qubit unitary operation \(U: U|ij\rangle = |\psi_{ij}\rangle\) on qubits \(A\) and \(A'\), where \(|\psi_{00}\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle), \)
\(|\psi_{11}\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle), \)
\(|\psi_{01}\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle), \)
\(|\psi_{10}\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle). \)
Then qubits \(A\) and \(A'\) each transmits through a PD channel, and the output state becomes \(\rho' = \Lambda^\text{PD} \otimes \Lambda^\text{PD} \otimes I_{BB'}(U_{AA'} \rho_{AA'} U_{AA'}^\dagger)\).
Now we check whether quantum correlation defined on \(AA'\) is created between the bipartition \(AA': BB'\) by using the criterion in Ref. [19]. Notice that
\[
[\Lambda^\text{PD} \otimes \Lambda^\text{PD}(\psi_{00}), \Lambda^\text{PD} \otimes \Lambda^\text{PD}(\psi_{11})] = \frac{1}{8} i p \sqrt{1-p} (I \otimes \delta_{\sigma y \otimes I} + \delta_{\sigma y \otimes I}) \neq 0, \tag{26}
\]
and consequently, quantum correlation is created between the bipartition \(AA': BB'\).

The super-activation of QCP is a collective effect. The reduced two-qubit states \(\tilde{\rho}_{AB}^{\prime} = \text{Tr}_{A'B'}(\rho') = (I_{A}/2) \otimes \rho_{B}^{\prime}\)
and \( \rho'_{A'B'} = \text{Tr}_{AB}(\rho') = (I_A'/2) \otimes \rho_{B'} \) are product states, which contain no correlations at all. The local two-qubit unitary operation \( U \) does not build correlations between qubits \( A \) and \( A' \), since reduced state of qubits \( A \) and \( A' \) remains completely mixed during the whole process. All in all, no correlation exists between any two qubits of the four-qubit state \( \rho' \). Therefore, we suppose that the effect of super-activation of QCP is due to the genuine quantum correlation.

VI. CONCLUSION

We have introduced the concept of quantum-correlating power for quantifying the ability of local quantum channel to generate quantum correlation from a classically correlated state. For any channel, the general form of the optimal input state has been proved to be the classical-classical state. Furthermore, the single-qubit channels with maximum QCP can be found in the class of local channels which takes a classical-classical state as the classical-classical state. For any channel, the generic expression for QCP of single-qubit AD channel has been obtained.

When two zero-QCP channels are used together, a positive-QCP channel can be obtained. We call this effect the super-activation of QCP. In the example of PD channel, we find a four-qubit state with genuine four-qubit quantum correlation but zero two-qubit correlation. This result should be helpful in the study of quantum correlating structure in multi-qubit states.

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