Decoherence suppression for three-qubit W-like state using weak measurement and iteration method*

Guang Yang(杨光)†, Bao-Wang Lian(廉保旺), and Min Nie(聂敏)

Department of Communication Engineering, School of Electronics and Information, Northwestern Polytechnical University, Xi'an 710072, *China*

(Received 18 March 2016; revised manuscript received 28 April 2016; published online 25 June 2016)

Multi-qubit entanglement states are the key resources for various multipartite quantum communication tasks. For a class of generalized three-qubit quantum entanglement, W-like state, we demonstrate that the weak measurement and the reversal measurement are capable of suppressing the amplitude damping decoherence by reducing the initial damping factor into a smaller equivalent damping factor. Furthermore, we propose an iteration method in the weak measurement and the reversal measurement to enhance the success probability of the total measurements. Finally, we discuss how the number of the iterations influences the overall effect of decoherence suppression, and find that the "half iteration" method is a better option that has more practical value.

Keywords: quantum decoherence, W-like state, amplitude damping, weak measurement

PACS: 03.67.Pp, 03.65.Yz, 03.67.Hk **DOI:** 10.1088/1674-1056/25/8/080310

1. Introduction

Quantum entanglement states are the critical resources needed in quantum computation and quantum communication, such as quantum teleportation,[1–3] quantum dense coding,[4–6] quantum key distribution,[7–10] quantum secure direct communication,[11–13] and quantum secret sharing.[14–16] However, a quantum state will couple with the environment inevitably, which brings quantum noise and breaks the coherence of quantum entanglement state, leading to the degradation or even the failure of quantum tasks.

Several methods have been proposed to overcome the influence of decoherence on quantum entanglements. Quantum entanglement purification is one of the most direct methods. The purification uses proper local operations and classical communications to extract a sub-ensemble with higher purity from a quantum ensemble polluted by noise.[17–19] Quantum error coding is another important method to solve the decoherence problem, which is used to recover the initial quantum information from the coded quantum messages by inserting some redundant information.[20–22] Recently, a strategy based on the so-called decoherence-free subspace has been proposed. This strategy utilizes a noiseless sub-space of the quantum Hilbert space to construct the quantum code that can avoid the decoherence.[23–25]

Weak measurement is a type of quantum measurement that would not cause the quantum system to fully collapse, thus the weak-measured system may be recovered through some reversal operations. The probabilistic reversing operation of an unsharp measurement was discussed in the context of quantum error correction.[26] Some researchers employed an additional weak measurement to implement the recovery and have experimentally demonstrated their methods on a single superconducting qubit, single photonic qubit and arbitrary cavity field states with finite photons.[27–29] Al-Amri *et al.* proposed an alternative way based on Hadamard and Controlled-NOT (CNOT) gates that can shorten the reversal time.[30] This approach was also discussed in Ref. [31] to recover an arbitrary pure two-qubit entanglement state that has undergone a weak measurement. Recently, Korotkov and Keane,[32] Kim *et al.*,[33] and Lee *et al.*[34] demonstrated that the weak measurement and the measurement reversal can protect the single qubit state and two-qubit entanglement state from the amplitude damping decoherence.

With the rapid development of quantum technology, multipartite communication will become an important form of quantum communication, whose realization is based on multi-qubit quantum entanglement states.[35–38] Current research about decoherence suppression for multi-qubit entanglement usually focuses on a few special quantum states, such as Greenberger–Horne–Zeilinger (GHZ) state and W state.[39–41] Based on Refs. [32]–[34], Liao *et al.*[42] used the weak measurement method and quantum measurement reversal to preserve the entanglement of three-qubit GHZ state and three-qubit W state, demonstrating that this method was capable of enhancing the negativity of the entanglement and the fidelity of teleportation. The three-qubit W-like state is a more general quantum entanglement state that has been used in many quantum communication schemes.[43–45] However, research on de-

*Project supported by the National Natural Science Foundation of China (Grant No. 61172071), the International Scientific Cooperation Program of Shaanxi Province, China (Grant No. 2015KW-013), and the Scientific Research Program Funded by Shaanxi Provincial Education Department, China (Grant No. 16JK1711).

†Corresponding author. E-mail: sharon.yg@163.com

© 2016 Chinese Physical Society and IOP Publishing Ltd

coherence suppression for W-like state is rather insufficient.

In this paper, we use the weak measurement and the reversal measurement to cope with the decoherence of three-qubit W-like state in the amplitude damping channel, and demonstrate that it is effective to improve the quality of the entanglement. Through the theoretical derivation, we obtain a more concise result to show the effect of the decoherence suppression. After the weak measurement and the reversal measurement, the initial damping factor of the amplitude damping channel is changed into another smaller damping factor, and we call it the equivalent damping factor. Unfortunately, if we want to obtain a smaller equivalent damping factor, we must increase the measurement strengths, which will eventually reduce the total success probability of the decoherence suppression. Further, to enhance the success probability, we propose a method of iterated measurements and analyze the influence of the number of the iterations on the success probability. Finally, we present a method called "half iteration" that is optimal for increasing the success probability when it obtains the same equivalent damping factor as other methods.

2. Influence of amplitude damping on W-like state

Amplitude damping is an important type of quantum decoherence, which can model many practical physical processes, such as spontaneous emission and super-conduction with zero-temperature energy relaxation. In an amplitude damping channel, the evolutions of a single qubit system state and the environment can be described as the following quantum transformation:[46]

$$U_{\mathrm{AD}}=\begin{cases}|0\rangle_{\mathrm{SYS}}|0\rangle_{\mathrm{ENV}}\rightarrow|0\rangle_{\mathrm{SYS}}|0\rangle_{\mathrm{ENV}},\\ |1\rangle_{\mathrm{SYS}}|0\rangle_{\mathrm{ENV}}\rightarrow\sqrt{1-\lambda}\,|1\rangle_{\mathrm{SYS}}|0\rangle_{\mathrm{ENV}},\\ \quad+\sqrt{\lambda}\,|0\rangle_{\mathrm{SYS}}|1\rangle_{\mathrm{ENV}},\end{cases}\tag{1}$$

where λ is the amplitude damping factor, SYS denotes the system, and ENV represents the environment. According to quantum noise theory, the Kraus operator of this channel can be given as

$$E_0=\begin{bmatrix}1&0\\0&\sqrt{1-\lambda}\end{bmatrix},\quad E_1=\begin{bmatrix}0&\sqrt{\lambda}\\0&0\end{bmatrix}.\tag{2}$$

The three-qubit W-like state is described as

$$|W_1\rangle=\alpha|100\rangle_{ABC}+\beta|010\rangle_{ABC}+\gamma|001\rangle_{ABC}.\tag{3}$$

The coefficients α, β, and γ are complexes that satisfy $|\alpha|^2+|\beta|^2+|\gamma|^2=1$. The subscripts A, B, and C denote different qubits of the W-like state. After suffering the amplitude damping, the evolution of the W-like state can be expressed as the following operator-sum representation:

$$\rho_1=\sum_{i,j,t=0,1}E_i^A\otimes E_j^B\otimes E_t^C\rho_0(E_i^A\otimes E_j^B\otimes E_t^C)^{\dagger}.\tag{4}$$

Here, ρ_0 is the density matrix of the initial pure state $|W_l\rangle$, E_i^A, E_j^B, and E_t^C are the Kraus operators on qubits A, B, and C, respectively. For the simplicity of analysis, we assume that each qubit of the W-like state undergoes amplitude damping with the same damping factor λ, then we obtain the following result:

$$\rho_1=\begin{bmatrix}\lambda&0&0&0&0&0&0&0\\0&(1-\lambda)|\gamma|^2&(1-\lambda)\gamma\beta^*&0&(1-\lambda)\gamma\alpha^*&0&0&0\\0&(1-\lambda)\beta\gamma^*&(1-\lambda)|\beta|^2&0&(1-\lambda)\beta\alpha^*&0&0&0\\0&0&0&0&0&0&0&0\\0&(1-\lambda)\alpha\gamma^*&(1-\lambda)\alpha\beta^*&0&(1-\lambda)|\alpha|^2&0&0&0\\0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0\\0&0&0&0&0&0&0&0\end{bmatrix}.\tag{5}$$

According to Eq. (5), we have $\rho_0=\rho_1|_{\lambda=0}$. Compare ρ_1 with ρ_0, then it will be easy to obtain the following equation:

$$\rho_1=(1-\lambda)\rho_0+\lambda|000\rangle\langle 000|.\tag{6}$$

That is to say, after suffering the amplitude damping, the W-like state lies in the initial state with probability $(1-\lambda)$ and turns into state $|000\rangle$ with probability λ.

From Eq. (6), the Bures fidelity of ρ_1 to ρ_0 can be calculated as

$$F(\rho_1,\rho_0)=\left[\mathrm{Tr}(\sqrt{\sqrt{\rho_0}\rho_1\sqrt{\rho_0}})\right]^2=1-\lambda.\tag{7}$$

3. Decoherence suppression for W-like state using weak measurement

In this part, we will discuss the effects of the weak measurement and the reversal measurement on the W-like state undergoing amplitude damping.

The weak measurement on a three-qubit system can be described as a tensor product of three non-unitary quantum operations, expressed as

$$M_{\mathrm{wk}}(p_1,p_2,p_3)=\begin{bmatrix}1&0\\0&\sqrt{1-p_1}\end{bmatrix}\otimes\begin{bmatrix}1&0\\0&\sqrt{1-p_2}\end{bmatrix}\otimes\begin{bmatrix}1&0\\0&\sqrt{1-p_3}\end{bmatrix},\tag{8}$$

where p_1, p_2, and p_3 are the weak measurement strengths on the three qubits of the W-like state respectively.

Before suffering amplitude damping, the weak measurement is performed on the initial W-like state. Then, the three qubits of the W-like state are distributed to the three remote users through amplitude damping channel. After that, the users carry out the three-qubit reversal measurement described as the following operation:

$$M_{\mathrm{rev}}(p_{\mathrm{r}1},p_{\mathrm{r}2},p_{\mathrm{r}3})=\begin{bmatrix}\sqrt{1-p_{\mathrm{r}1}}&0\\0&0\end{bmatrix}\otimes\begin{bmatrix}\sqrt{1-p_{\mathrm{r}2}}&0\\0&0\end{bmatrix}$$

$$\otimes \begin{bmatrix} \sqrt{1-p_{r3}} & 0 \\ 0 & 0 \end{bmatrix}, \tag{9}$$

where p_{r1}, p_{r2}, and p_{r3} are the reversal measurement strengths and satisfy the optimal reversing condition:

$$p_{ri} = p_i + \lambda(1-p_i). \tag{10}$$

Considering the assumption that the three qubits of the W-like state have the same amplitude damping factor λ, let $p_1 = p_2 = p_3 = p$, then $p_{r1} = p_{r2} = p_{r3} = p_r$. After the weak measurement, the amplitude damping and the reversal measurement above, the initial pure W-like state will evolve into a mixed state having the following density matrix:

$$\rho_2 = \frac{1}{L}\begin{bmatrix} \mu_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu_2 & \mu_3 & 0 & \mu_4 & 0 & 0 & 0 \\ 0 & \mu_3^* & \mu_5 & 0 & \mu_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \mu_4^* & \mu_6^* & 0 & \mu_7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \tag{11}$$

where

$$\begin{aligned} \mu_1 &= \lambda(1-p)(1-p_r)^3, \\ \mu_2 &= (1-\lambda)(1-p)(1-p_r)^2|\gamma|^2, \\ \mu_3 &= (1-\lambda)(1-p)(1-p_r)^2\gamma\beta^*, \\ \mu_4 &= (1-\lambda)(1-p)(1-p_r)^2\gamma\alpha^*, \\ \mu_5 &= (1-\lambda)(1-p)(1-p_r)^2|\beta|^2, \\ \mu_6 &= (1-\lambda)(1-p)(1-p_r)^2\beta\alpha^*, \\ \mu_7 &= (1-\lambda)(1-p)(1-p_r)^2|\alpha|^2, \\ L &= (1-p)(1-p_r)^2(1-\lambda p_r). \end{aligned} \tag{12}$$

The total success probability of the weak measurement and the reversal measurement is

$$P_S = (1-p)(1-p_r)^2(1-\lambda p_r). \tag{13}$$

Comparing Eq. (11) with Eq. (5), we can derive the following result:

$$\rho_2 = (1-\lambda_{ev})\rho_0 + \lambda_{ev}|000\rangle\langle 000|. \tag{14}$$

Equation (14) means that for the W-like state, the weak measurement and the reversal measurement change the initial amplitude damping channel into an equivalent amplitude damping channel with a smaller damping factor as

$$\lambda_{ev} = \frac{(1-p_r)}{(1-\lambda p_r)}\lambda \le \lambda. \tag{15}$$

Here, λ_{ev} is called the equivalent damping factor. The Bures fidelity of ρ_2 to ρ_0 is

$$F(\rho_2,\rho_0) = \left[\mathrm{Tr}\left(\sqrt{\sqrt{\rho_0}\rho_2\sqrt{\rho_0}}\right)\right]^2 = 1-\lambda_{ev}. \tag{16}$$

Obviously, $F(\rho_2,\rho_0)$ is higher than $F(\rho_1,\rho_0)$, showing that the weak measurement and the reversal measurement can suppress the decoherence of W-like state effectively.

The equivalent damping factor λ_{ev} of the weak measurement and the reversal measurement, varying with p and λ is shown in Fig. 1. It can be seen from Fig. 1 that, given a specific λ, a smaller λ_{ev} can be obtained in the case of a stronger weak measurement strength p; while given a specific p, λ_{ev} increases with the increase of λ.

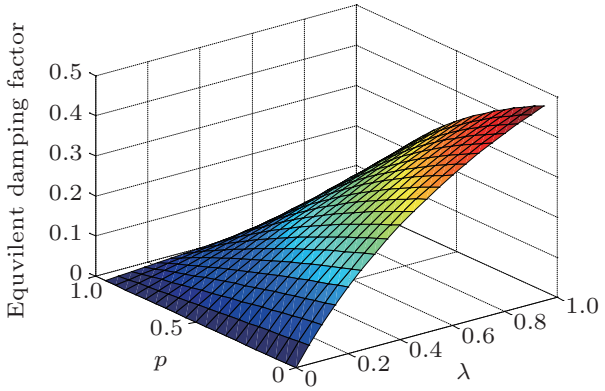


Fig. 1. (color online) Equivalent damping factor of the weak measurement and the reversal measurement.

The total success probability P_S of the weak measurement and the reversal measurement is shown in Fig. 2. From this figure we can see that P_S decreases with p and λ increasing. This means that if we want to obtain a smaller λ_{ev} by increasing p, then we will obtain a smaller success probability, and P_S will be much smaller in the case of larger λ, which leads to a great consumption of the quantum entanglement resources.

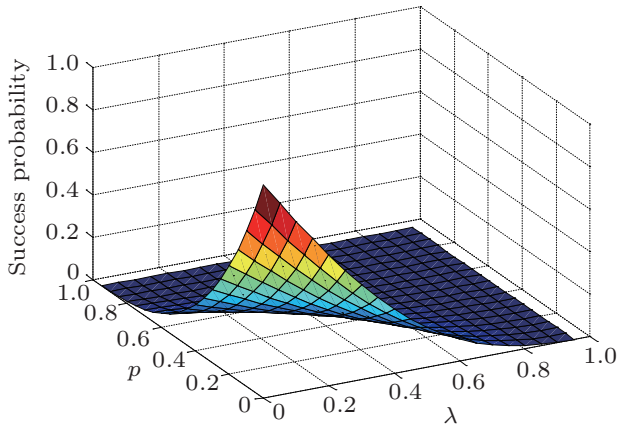


Fig. 2. (color online) Total success probability of the weak measurement and the reversal measurement.

According to this problem, we try to find whether the success probability could be raised to some extent and thus to improve the overall performance of the decoherence suppression scheme above. This will be discussed below.

4. Improvement in success probability via iterated measurements

We consider Eq. (15) again and change it into the following expression:

$$\lambda_{\rm ev} = \frac{(1-p_{\rm r})}{\lambda(1-p_{\rm r})+(1-\lambda)}\lambda. \tag{17}$$

Equation (17) means that a smaller $(1-p_{\rm r})$ will lead to a smaller $\lambda_{\rm ev}$ in the case of a given λ. Based on this thinking, if the weak measurement and the reversal measurement are carried out several times, a smaller measurement strength pair $(p, p_{\rm r})$ would be needed to obtain an equal $\lambda_{\rm ev}$, which may lead to a larger success probability.

If we perform a weak measurement successfully with strength p, then we repeat the weak measurement once with the same strength p; and if the corresponding reversal measurement is successful with strength $p_{\rm r}$, we repeat the reversal measurement once with the same strength $p_{\rm r}$. A pair of repeated operations above is called one iteration. The total measurements with one iteration are described as

$$\begin{aligned} M_{\rm wk-2}(p') &= \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p'} \end{bmatrix}^2 \otimes \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p'} \end{bmatrix}^2 \\ &\quad \otimes \begin{bmatrix} 1 & 0 \\ 0 & \sqrt{1-p'} \end{bmatrix}^2, \\ M_{\rm rev-2}(p'_{\rm r}) &= \begin{bmatrix} \sqrt{1-p'_{\rm r}} & 0 \\ 0 & 0 \end{bmatrix}^2 \otimes \begin{bmatrix} \sqrt{1-p'_{\rm r}} & 0 \\ 0 & 0 \end{bmatrix}^2 \\ &\quad \otimes \begin{bmatrix} \sqrt{1-p'_{\rm r}} & 0 \\ 0 & 0 \end{bmatrix}^2, \end{aligned} \tag{18}$$

where p' and $p'_{\rm r}$ are used to denote the measurements with and without iteration respectively, and they also satisfy the optimal reversing condition $p'_{\rm r} = p' + \lambda(1-p')$.

After the iterated weak measurement, the amplitude damping and the iterated reversal measurement, the pure W-like state evolves into a mixed state whose density matrix (denoted as ρ_3) has a similar form to Eq. (11). The corresponding elements of the matrix ρ_3 are

$$\begin{aligned} \mu'_1 &= \lambda(1-p')^2(1-p'_{\rm r})^6, \\ \mu'_2 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4|\gamma|^2, \\ \mu'_3 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4\gamma\beta^*, \\ \mu'_4 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4\gamma\alpha^*, \\ \mu'_5 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4|\beta|^2, \\ \mu'_6 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4\beta\alpha^*, \\ \mu'_7 &= (1-\lambda)(1-p')^2(1-p'_{\rm r})^4|\alpha|^2, \\ L' &= (1-p')^2(1-p'_{\rm r})^4[(1-\lambda)+\lambda(1-p'_{\rm r})^2]. \end{aligned} \tag{19}$$

The total success probability of the operations above is

$$P'_{\rm S} = (1-p')^2(1-p'_{\rm r})^4[(1-\lambda)+\lambda(1-p'_{\rm r})^2]. \tag{20}$$

Then, we can obtain the following result:

$$\rho_3 = (1-\lambda'_{\rm ev})\rho_0 + \lambda'_{\rm ev}|000\rangle\langle 000|, \tag{21}$$

where the equivalent damping factor is

$$\lambda'_{\rm ev} = \frac{(1-p'_{\rm r})^2}{\lambda(1-p'_{\rm r})^2+(1-\lambda)}\lambda \le \lambda. \tag{22}$$

Comparing Eq. (22) with Eq. (17), if we want to obtain the same equivalent damping factors through using the measurements without iteration as the iterated measurements, the reversal measurement strength must meet the following conditions:

$$p_{\rm r} = 1-(1-p'_{\rm r})^2. \tag{23}$$

From Eq. (23), considering the optimal reversing condition $p'_{\rm r} = p' + \lambda(1-p')$ and $p_{\rm r} = p + \lambda(1-p)$, the weak measurement strength should satisfy

$$p = \frac{[1-(1-p'+\lambda p'-\lambda)^2]-\lambda}{1-\lambda}. \tag{24}$$

When we choose the measurement strength pair $(p,\ p_{\rm r})$ described in Eqs. (23) and (24) to perform the measurements without iteration, the total success probability can be obtained according to Eq. (13).

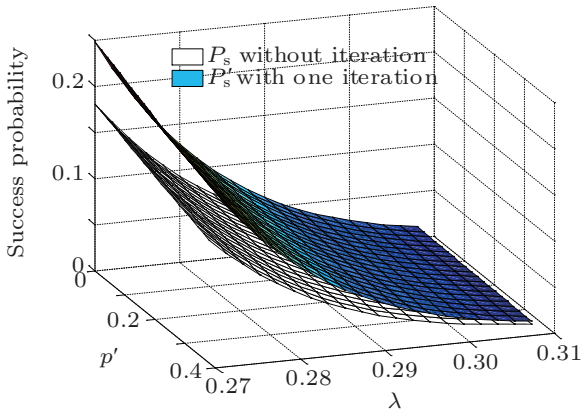


Fig. 3. (color online) Comparison between the success probabilities obtained by the method with one iteration and those by the method without iteration.

Figure 3 shows the comparison between the success probabilities obtained using the method without iteration and those using the method with one iteration when both methods obtain the same equivalent damping factors, and the corresponding equivalent damping factors are shown in Fig. 4. In Figs. 3 and 4, the X axis means the initial amplitude damping factor and the Y axis represents the iterated weak measurement strength. Obviously, using iterated measurements has a higher success probability.

On the other hand, if we want to obtain the same success probabilities by using the two methods, then the following condition should be satisfied according to Eqs. (13) and (20):

$$(1-p)(1-p_{\rm r})^2(1-\lambda p_{\rm r})$$

$$= (1-p')^2(1-p'_{\rm r})^4[(1-\lambda)+\lambda(1-p'_{\rm r})^2]. \quad (25)$$

Let $X = 1-p_{\rm r}$ and $Y = (1-p'_{\rm r})^2$, equation (25) can be changed into the following form:

$$(1-\lambda)X^3(1-\lambda+\lambda X) = Y^3(1-\lambda+\lambda Y). \quad (26)$$

To make Eq. (26) hold true, the condition $X \geq Y$ must be satisfied. Then, from Eqs. (17) and (22), we have

$$\lambda'_{\rm ev} < \lambda_{\rm ev}. \quad (27)$$

The results above show that the measurements with one iteration can increase the success probability of the decoherence suppression and enhance the entanglement fidelity of the three-qubit W-like state compared with the measurements without iteration.

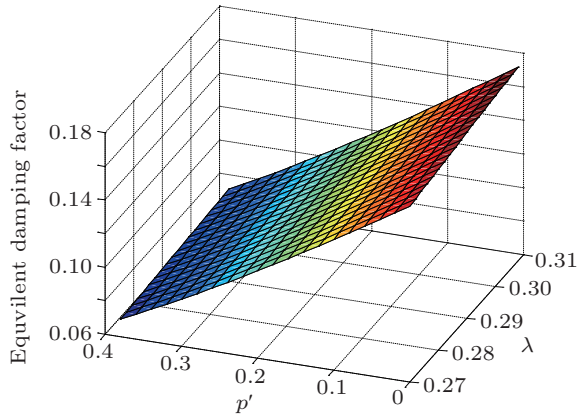


Fig. 4. (color online) Equivalent damping factors obtained by the method with one iteration and by the method without iteration

5. Discussion

5.1. Measurements with more iterations

Since iteration can improve the overall performance of the weak measurement and the reversal measurement, is it true that we can obtain better results via increasing the number of the iterations? Given a measurement strength pair $(p'', p''_{\rm r})$, we perform three iterations by a similar method to that in Section 4. The equivalent damping factor can be obtained as follows:

$$\lambda''_{\rm ev} = \frac{(1-p''_{\rm r})^4}{\lambda(1-p''_{\rm r})^4+(1-\lambda)}\lambda. \quad (28)$$

The success probability of the measurements with three iterations is

$$P''_{\rm S} = (1-p'')^4(1-p''_{\rm r})^8[(1-\lambda)+\lambda(1-p''_{\rm r})^4]. \quad (29)$$

Figure 5 shows the comparison among the success probabilities obtained by three methods, i.e., the method with three iterations, the method with one iteration, and the method without iteration respectively, when they obtain the same equivalent damping factors. From this figure it follows that the method with three iterations obtains the highest success probability, but the success probability is quite small even if the weak measurement strength p'' is close to zero. For example, when damping factor $\lambda = 0.27$ and $p'' = 0$, the success probability of the measurements with three iterations is 0.0651, and the entanglement fidelity is 0.9049. This result shows that when we want to obtain a very high entanglement fidelity by increasing the strengths of the measurements or the number of the iterations, the success probability will be very small. So the excess number of the iterations is of no practical value because of the excessive consumption of the initial W-like entanglement states. This may result in a very low yield of the decoherence suppression.

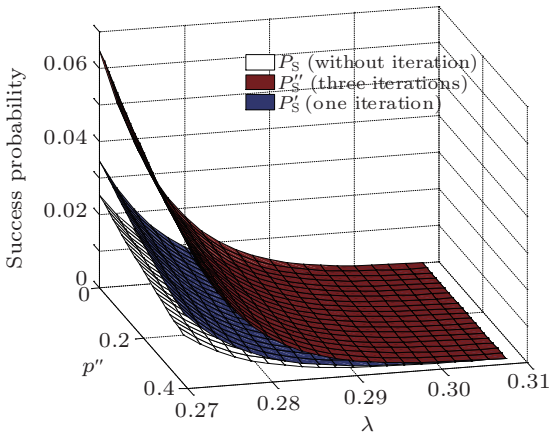


Fig. 5. (color online) Comparison among the success probabilities obtained by the method with three iterations, the method with one iteration, and the method without iteration, respectively.

5.2. Increase of the success probability of the iteration

Consider Eq. (20) again. We can see that the success probability of the measurements with one iteration decreases with the decease of $(1-p')^2$. If we perform the weak measurement without iteration and the reversal measurement with one iteration, we call this "half iteration", then the success probability is changed into

$$P^{\circ}_{\rm S} = (1-p')(1-p'_{\rm r})^4[(1-\lambda)+\lambda(1-p'_{\rm r})^2]. \quad (30)$$

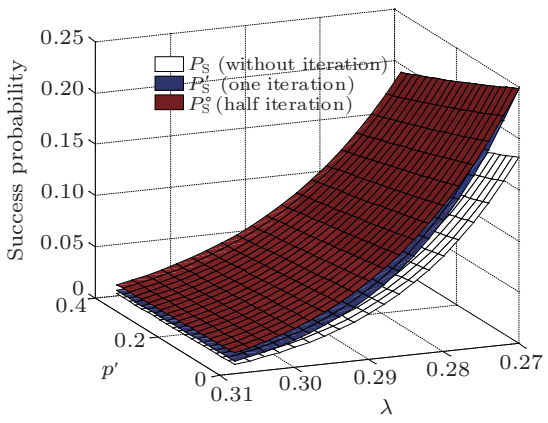


Fig. 6. (color online) Comparison among the success probabilities of the method with half iteration, the method with one iteration, and the method without iteration, respectively.

Using this half iteration method, the equivalent damping factor can also be calculated by using Eq. (22).

Figure 6 shows the comparison among the success probabilities obtained by the method with one iteration, the method with half iteration, and the method without iteration respectively. From the figure we can see that the method with half iteration obtains the highest success probabilities when the three methods obtain the same equivalent damping factors.

6. Conclusions

In this paper, we show theoretically that decoherence of the three-qubit W-like state undergoing amplitude damping can be suppressed by weak measurement and the reversal measurement. Given an initial damping factor λ, this method is capable of reducing λ to a smaller equivalent damping factor $\lambda_{\rm ev}$, which is related to the measurement strength. By increasing the measurement strength, we can obtain a smaller $\lambda_{\rm ev}$, but the total success probability of the measurements will decrease quickly at the same time. To solve this problem, we propose a method of iterated measurements and demonstrate that it is useful to increase the success probability when its equivalent damping factor is equal to the $\lambda_{\rm ev}$ of the measurements without iteration. With increasing the iteration number, the equivalent damping factor becomes smaller and the success probability also becomes smaller. We find that the iteration number bigger than three has no practical significance because of the low yield, whereas another method called half iteration is a better option that has the optimal overall effects.

References

[1] Bennett C H, Brassard G, Crépeau C, Jozsa R, Peres A and Wootters W K 1993 *Phys. Rev. Lett.* **70** 1895

[2] Bouwmeester D, Pan J W, Mattle K, Eibl M, Weinfurter H and Zeilinger A 1997 *Nature* **390** 575

[3] Yonezawa H, Aoki T and Furusawa A 2004 *Nature* **431** 430

[4] Mattle K, Weinfurter H, Kwiat P G and Zeilinger A 1996 *Phys. Rev. Lett.* **76** 4656

[5] Liu X S, Long G L, Tong D M and Li F 2002 *Phys. Rev. A* **65** 022304

[6] Ye L and Guo G C 2005 *Phys. Rev. A* **71** 034304

[7] Jennewein T, Simon C, Weihs G, Weinfurter H and Zeilinger A 2000 *Phys. Rev. Lett.* **84** 4729

[8] Long G L and Liu X S 2002 *Phys. Rev. A* **65** 032302

[9] Curty M, Lewenstein M and Lütkenhaus N 2004 *Phys. Rev. Lett.* **92** 217903

[10] Madsen L S, Usenko V C, Lassen M, Filip R and Andersen U L 2012 *Nat. Commun.* **3** 1083

[11] Wang C, Deng F G, Li Y S, Liu X S and Long G L 2005 *Phys. Rev. A* **71** 044305

[12] Man Z X, Zhang Z J and Li Y 2005 *Chin. Phys. Lett.* **22** 18

[13] Lin S, Wen Q Y, Gao F and Zhu F C 2008 *Phys. Rev. A* **78** 064304

[14] Hillery M, Bužek V and Berthiaume A 1999 *Phys. Rev. A* **59** 1829

[15] Zhang Z J, Li Y and Man Z X 2005 *Phys. Rev. A* **71** 044301

[16] Helwig W, Cui W, Latorre J I, Riera A and Lo H K 2012 *Phys. Rev. A* **86** 052335

[17] Pan J W, Simon C, Brukner Č and Zeilinger A 2001 *Nature* **410** 1067

[18] Ren B C, Du F F and Deng F G 2014 *Phys. Rev. A* **90** 052309

[19] Yang G, Lian B W and Nie M 2015 *Acta Phys. Sin.* **64** 010303 (in Chinese)

[20] Shor P W 1995 *Phys. Rev. A* **52** 2493

[21] Wang Y J, Bai B M, Li Z, Peng J Y and Xiao H L 2012 *Chin. Phys. B* **21** 020304

[22] Terhal B M 2015 *Rev. Mod. Phys.* **87** 307

[23] Li C K, Nakahara M, Poon Y T, Sze N S and Tomita 2011 *Phys. Rev. A* **84** 044301

[24] Xu G F, Zhang J, Tong D M, Sjöqvist E and Kwek L C 2012 *Phys. Rev. Lett.* **109** 170501

[25] Liu A P, Cheng L Y, Chen L, Su S L, Wang H F and Zhang S 2014 *Opt. Commun.* **313** 180

[26] Koashi M and Ueda M 1999 *Phys. Rev. Lett.* **82** 2598

[27] Korotkov A N and Jordan A N 2006 *Phys. Rev. Lett.* **97** 166805

[28] Katz N, Neeley M, Ansmann M, Bialczak R C, Hofheinz M, Lucero E, Connell A O, Wang H, Cleland A N, Martinis J M and Korotkov A N 2008 *Phys. Rev. Lett.* **101** 200401

[29] Sun Q, Al-Amri M and Zubairy M S 2009 *Phys. Rev. A* **80** 033838

[30] Al-Amri M, Scully M O and Zubairy M S 2011 *J. Phys. B: At. Mol. Opt. Phys.* **44** 165509

[31] Liao Z, Al-Amri M and Zubairy M S 2013 *J. Phys. B: At. Mol. Opt. Phys.* **46** 145501

[32] Korotkov A N and Keane K 2010 *Phys. Rev. A* **81** 040103

[33] Kim Y S, Lee J C, Kwon O and Kim Y H 2012 *Nat. Phys.* **8** 117

[34] Lee J C, Jeong Y C, Kim Y S and Kim Y H 2011 *Opt. Express* **19** 16309

[35] Sheng Y B, Zhou L and Zhao S M 2012 *Phys. Rev. A* **85** 042302

[36] Hwang T, Hwang C C and Li C M 2011 *Phys. Scr.* **83** 045004

[37] Liu W, Wang Y B and Jiang Z T 2011 *Opt. Commun.* **284** 3160

[38] Zhang W W and Zhang K J 2013 *Quantum Infor. Process.* **12** 1981

[39] Xu G B, Wen Q Y, Gao F and Qin S J 2014 *Quantum Infor. Process.* **13** 2587

[40] Cao Z L and Yang M 2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** 4245

[41] Ren B C, Du F F and Deng F G 2014 *Phys. Rev. A* **90** 052309

[42] Liao X P, Fang M F, Fang J S and Zhu Q Q 2014 *Chin. Phys. B* **23** 020304

[43] Lin X and Li H C 2005 *Chin. Phys.* **14** 1724

[44] Zheng S B 2006 *Phys. Rev. A* **74** 054303

[45] Tsai C W and Hwang T 2010 *Opt. Commun.* **283** 4397

[46] Nielsen M A and Chuang I L 2000 *Quantum Computation and Quantum Information* (Cambridge: Cambridge University Press)