Counterfactual Long-Distance Quantum Communication

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***Abstract*—Long-distance quantum communication holds significant promises for information transmission over extremely large distances. However, ensuring communication security over extensive distances poses considerable challenges. In this article, we propose a new approach to long-distance quantum communication, which is carried out in a information-carrying particle-free manner, known as counterfactual quantum communication. Our approach extends the counterfactual transmission signal by leveraging quantum repeaters situated between distant nodes, facilitating counterfactual entanglement swapping. Due to the absence of information-carrying particles in the channel, it enhances the security of information transmission. We demonstrate that our proposed protocol not only establishes the direct communication link between distant nodes, but also generates redundant communication links between neighboring nodes, enhancing resilience against primary link failures. Furthermore, we provide numerical simulations of C-Swap gate and counterfactual long-distance quantum communication scenarios to quantify success probabilities where the photon is not lost during the counterfactual communication.**

***Index Terms*—Long-distance, counterfactual quantum communication, C-Swap gate, counterfactual entanglement swapping, quantum repeaters.**

I. Introduction

Photons have been widely used as quantum information carriers in free-space optical communication or fiber network structures [1], [2]. Their widespread adoption is attributed to their simplicity in generation and the ability to prepare and manipulate quantum states of light using standard optical components. Quantum key distribution (QKD) is one of the first and most prominent applications of photons in quantum information processing [3], [4]. In QKD, information is encoded in the quantum state of single photons, enabling secure communication [5]. However, the distance over which photons can effectively travel is constrained to just a few tens of kilometers, primarily due to signal degradation caused by scattering and absorption phenomena [6]. This limit their utilization in long-distance quantum communication across continental scales, owing to the exponential decay of communication rate. To overcome this obstacle, the deployment of quantum repeaters at strategic intervals along the communication cable becomes imperative. These repeaters serve to amplify the signal, compensating for signal decay and facilitating long-distance quantum communication .

Long-distance quantum communication is essential for the development and functionality of quantum networks, providing unparalleled security through quantum cryptography and enabling the transmission of sensitive information over vast distances [7]. Extensive research efforts have been devoted on long-distance quantum communication over integrated space-to-ground quantum communication network, satellite-relayed intercontinental quantum network, etc. [8]–[10]. With the capability to establish communication channels between continents, long-distance quantum communication holds vast potential for global applications in diverse sectors, including finance, government, and scientific research by leveraging fundamental quantum principles such as superposition, entanglement, and interference.

The importance of long-distance quantum communication is further highlighted by its theoretical foundation of unconditional security. It stems from the impossibility of perfectly copying the quantum state transmitted through the channel, a principle upheld by the quantum no-cloning theorem [11]. Additionally, the intrinsic characteristics of quantum entanglement contribute to on-site eavesdropping detection capabilities in quantum communication, further enhancing security measures [12]. Nonetheless, eavesdropper may get hold of the communication channel through attacks such as man-in-the-middle attack or photon splitting attack. While these attempts are detectable, current implementations of quantum communication might have vulnerabilities. For instance, in the Ping Pong quantum communication protocol used for the secure transmission between two parties, eavesdroppers can steal the information without being exposed using ghost photons [13]. This attack is made possible thorough a new mode of quantum communication known as counterfactual quantum communication, which relies on the non-transmission of information carrying particles in the channel [14], [15].

The idea of counterfactual quantum communication emerges from the intriguing concept of interaction free measurement (IFM) and quantum Zeno (QZ) effect. IFM allows one to infer the presence of an absorptive object (AO) in a certain region without interacting with it [16], [17]. Elitzur–Vaidman bomb

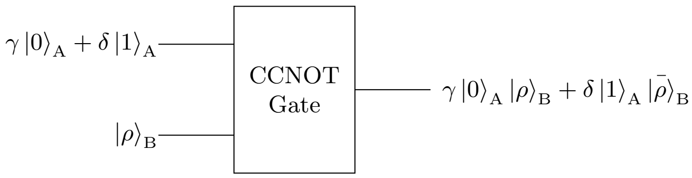


Fig. 1. A counterfactual controlled NOT (CCNOT) gate which enables the CNOT operation between Alice (control) and Bob (target), without the non-transmission of information carrying particle in the channel.

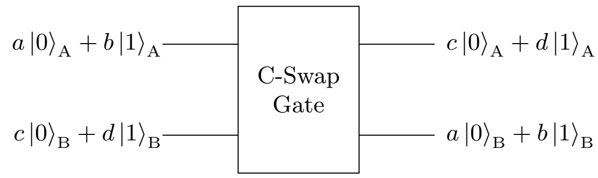


Fig. 2. A counterfactual swap (C-Swap) gate which swaps the qubits of Alice and Bob without any information-carrying particle passing through the channel.

tester is a thought experiment on IFM which demonstrates the ability to detect the presence of the bomb with 25% without explosion [18]. Later, QZ effect, which suppresses the evolution of quantum system, was exploited in IFM to achieve a detection probability of 100% [19]. However, this intergration of QZ effect with IFM guarantees counterfactuality only for the absence of AO (bit '0'). Thus, a nested version of QZ gate, known as chained quantum Zeno (CQZ) gate, is utilized to realize the counterfactual communication for both absence and presence of AO (bit '0' and '1'). Counterfactual quantum communication has been employed in various communication scenarios including cryptography, computation, duplex coding, concealed telecomputation, Bell state analyzer, anonymous teleportation and so on [20]–[25].

In this article, we propose a counterfactual approach to long-distance quantum communication, using counterfactual entanglement swapping enabled by C-Swap gate and quantum repeaters. As no information-carrying particle is passing through the channel during the communication, it provides ultra security compared to the conventional quantum communication. In addition, our proposed scheme not only establishes the direct communication link between the distant end parties, but also generates redundant communication links between adjacent nodes. These redundant links can compensate for the failure of the primary communication link. The rest of the paper is structured as follows. Section II provides the preliminaries required for the implementation of our proposed protocol. Section III presents the system model of our proposed protocol along with counterfactual entanglement swapping and counterfactual long-distance quantum communication. This is followed by the numerical results in Section IV. Finally, the conclusion and future research directions are discussed in Section V.

II. Preliminaries

A. CCNOT Gate

The counterfactual controlled NOT (CCNOT) gate allows Alice to perform a CNOT operation on a remote party, Bob, without the need of any information carrying particle passing through the channel. This is achieved through the utilization of a chained quantum Zeno (CQZ) gate. Here, Alice holds a quantum absorptive object (QAO) which acts as a control qubit, while Bob prepares a photon which act as a target qubit. Bob's photon can be horizontally or vertically polarized ($|0(1)\rangle_{\rm B}$), or it can exist in a superposition of both states ($|\rho\rangle_{\rm B} = \alpha |0\rangle_{\rm B} + \beta |1\rangle_{\rm B}$). For photons in the $|0(1)\rangle$ states, the operation employs an H(V)-CQZ gate, whereas for superposition states, a dual CQZ (DCQZ) gate is utilized [21]. The CCNOT gate with a superposition photon input transforms an initial state

$$|\psi_0\rangle = (\gamma |0\rangle_{\rm A} + \delta |1\rangle_{\rm A}) |\rho\rangle_{\rm B} \tag{1}$$

to

$$|\psi_1\rangle = \gamma |0\rangle_{\rm A} |\rho\rangle_{\rm B} + \delta |1\rangle_{\rm A} |\bar{\rho}\rangle_{\rm B} \tag{2}$$

with probability

$$p = \left(1 - \frac{1}{2}\sin^2\theta_M\right)^M \prod_{i=1}^{M} \left(1 - \frac{1}{2}\sin^2 i\theta_M \sin^2\theta_N\right)^N, \tag{3}$$

where the subscripts $\rm A$ and $\rm B$ denotes the qubits owned by Alice and Bob, and N and M represent the number of inner and outer cycles utilized in each CQZ gate.

B. C-Swap Gate

The counterfactual-Swap (C-Swap) gate plays a crucial role in quantum information processing tasks by enabling the counterfactual telexchange of one qubit of information in each direction between two remote parties, Alice and Bob. In contrast to conventional quantum Swap gate, the C-Swap gate ensures enhanced security as it eliminates the need of information-carrying particles passing through the communication channel. The process of qubit swapping with the C-Swap gate can be achieved by utilizing the dual D-CNOT operation [21].

Initially, Alice prepares a QAO represented by $a |0\rangle_{\rm A} + b |1\rangle_{\rm A}$, while Bob prepares a photon described by $c |0\rangle_{\rm B} + d |1\rangle_{\rm B}$, with $|a|^2 + |b|^2 = |c|^2 + |d|^2 = 1$. To initiate the protocol, Bob prepares an ancillary qubit $|0\rangle_{\rm C}$ and and performs a local CNOT operation on his qubit (control) and the ancillary qubit (target). Next, Alice and Bob execute two sequences of nonlocal CNOT operations where Alice's qubit acts as the control qubit in the first sequence and Bob's qubit acts as the target qubit in the second sequence. Following this, Bob performs another local CNOT operation with his auxillary qubit being the control qubit. Finally, to disentangle his auxiliary qubit, Bob applies Hadamard operation, measures it in the computational basis and announce the outcome. If the outcome is 1, Alice applies Puali-Z operation on her qubit. This procedure can be represented mathematically as follows:

$$(a|0\rangle_{\mathrm{A}}+b|1\rangle_{\mathrm{A}})\otimes(c|0\rangle_{\mathrm{B}}+d|1\rangle_{\mathrm{B}})\otimes|0\rangle_{\mathrm{C}}$$
$$\xrightarrow{\mathrm{CNOT}_{\mathrm{B}\to\mathrm{C}}}(a|0\rangle_{\mathrm{A}}+b|1\rangle_{\mathrm{A}})\otimes(c|00\rangle_{\mathrm{BC}}+d|11\rangle_{\mathrm{BC}})$$
$$\xrightarrow{\text{nonlocal CNOT}_{\mathrm{A}\to\mathrm{B}}}ac|000\rangle+ad|011\rangle+bc|110\rangle+bd|101\rangle$$
$$\xrightarrow{\text{nonlocal CNOT}_{\mathrm{B}\to\mathrm{A}}}ac|000\rangle+ad|111\rangle+bc|010\rangle+bd|101\rangle$$
$$\xrightarrow{\mathrm{CNOT}_{\mathrm{C}\to\mathrm{B}}}(c|00\rangle_{\mathrm{AC}}+d|11\rangle_{\mathrm{AC}})\otimes(a|0\rangle_{\mathrm{B}}+b|1\rangle_{\mathrm{B}})$$
$$\xrightarrow{\boldsymbol{H}\text{ \& Mea on C}}(c|0\rangle_{\mathrm{A}}+d|1\rangle_{\mathrm{A}})\otimes(a|0\rangle_{\mathrm{B}}+b|1\rangle_{\mathrm{B}}) \quad (4)$$

If the photon is not lost to the QAO during the C-Swap operation, the success probability of C-Swap gate can be expressed as [21]

$$q=\left(1-\frac{1}{2}\sin^2\theta_M\right)^M \prod_{i=1}^{M}\left(1-\frac{1}{2}\sin^2 i\theta_M\sin^2\theta_N\right)^N \left[\left(1-\frac{1}{2}\cos^2\theta_R\sin^2\theta_N\right)^N \left(1-\frac{1}{2}\sin^2\theta_R\right)\right]^R \quad (5)$$

where N, M and R denotes the number of inner cycles, outer cycles and the number of D-MQZ operations respectively. As N, M and R increases, the success probability q approaches to 1.

III. System Model

Long-distance quantum communication holds immense significance in quantum networks, allowing for communication between distant parties. At it cores, it is comprised of intermediate nodes, known as repeaters, that are capable of storing and processing quantum information. These repeaters are responsible for regenerating entanglement between adjacent nodes, progressively extending the communication range. The conventional long-distance quantum communication involves the transmission of particles through the communication channel, leaving vulnerabilities for potential eavesdropping. In this article, we propose a counterfactual approach to long-distance quantum communication, which operates in a particle-free manner. Additionally, studies have shown that conventional quantum communication is susceptible to counterfactual Trojan Horse attack which utilizes ghost photons [13]. By adopting a counterfactual approach, the security of long-distance communication is enhanced compared to conventional methods.

Fig. 3 describes the system model of our proposed counterfactual long-distance quantum communication. This model incorporates C-Swap gates to enable counterfactual entanglement swapping between adjacent nodes. In addition to the establishment of entanglement between two distant parties, Alice and Bob, our proposed scheme also generates redundant communication links between adjacent nodes, thereby providing an alternative route for transmitting information in case the primary communication link fails or experiences disruptions. We first demonstrate the counterfactual entanglement swapping in Section III-A, and then we present our proposed scheme in Section III-B.

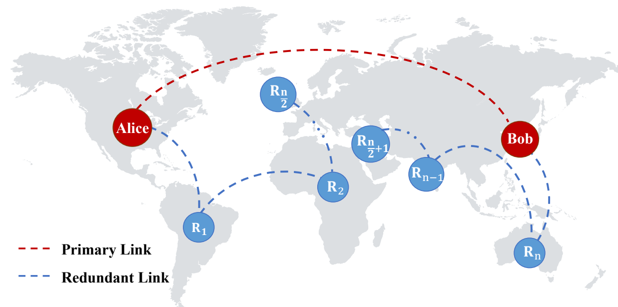


Fig. 3. System model of proposed scheme. R_i denotes repeater$_i$ where $i \in (1, 2, \ldots, n)$. Counterfactual entanglment swapping is performed at each repeater. Our proposed scheme not only enables the direct counterfactual long-distance quatnum communicaiton link (primary link), reprented by red line, between Alice and Bob, but also generates redundant counterfactual quantum communication links, represented by blue lines, between adjacent nodes.

A. Counterfactual Entanglement Swapping

As discussed in Section II-A, the C-Swap gate allows for the swapping of single qubits prepared by Alice and Bob. This gate's functionality can be expanded to enable counterfactual entanglement swapping (CES) between Alice and Bob, where they prepare entangled states instead of single qubit states. Entanglement swapping is particularly crucial in the context of long-distance quantum communication, as it facilitates the establishment of connections between particles that have never directly interacted before. In this context, Alice and Bob prepare Bell-like entangled pairs denoted as $|\phi_0\rangle_{\mathrm{a_1a_2}}$ and $|\phi_1\rangle_{\mathrm{b_1b_2}}$ respectively, and then input only one qubit from their pairs into the C-Swap gate. The entangled pairs prepared by Alice and Bob are represented as

$$|\phi_0\rangle_{\mathrm{a_1a_2}}=\alpha|00\rangle_{\mathrm{a_1a_2}}+\beta|11\rangle_{\mathrm{a_1a_2}} \quad (6)$$
$$|\phi_1\rangle_{\mathrm{b_1b_2}}=\gamma|00\rangle_{\mathrm{b_1b_2}}+\delta|11\rangle_{\mathrm{b_1b_2}} \quad (7)$$

where $\alpha, \beta, \gamma,$ and δ are complex coefficients and $|\alpha|^2+|\beta|^2=|\gamma|^2+|\delta|^2=1$ Here, the subscripts $\mathrm{a_1a_2}$ and $\mathrm{b_1b_2}$ denote the qubits belonging to Alice and Bob, respectively.

The initial state of the system before the C-Swap gate can be written as

$$|\eta_0\rangle=|\phi_0\rangle_{\mathrm{a_1a_2}}|\phi_1\rangle_{\mathrm{b_1b_2}}. \quad (8)$$

Suppose that Alice inputs her qubit $\mathrm{a_2}$ and Bob inputs his qubit $\mathrm{b_1}$ to the C-Swap gate. After the C-Swap gate, $|\eta_0\rangle$ transforms into

$$|\eta_1\rangle=|\phi_0\rangle_{\mathrm{a_1b_1}}|\phi_1\rangle_{\mathrm{a_2b_2}}, \quad (9)$$

where the qubits of Alice and Bob become entangled.

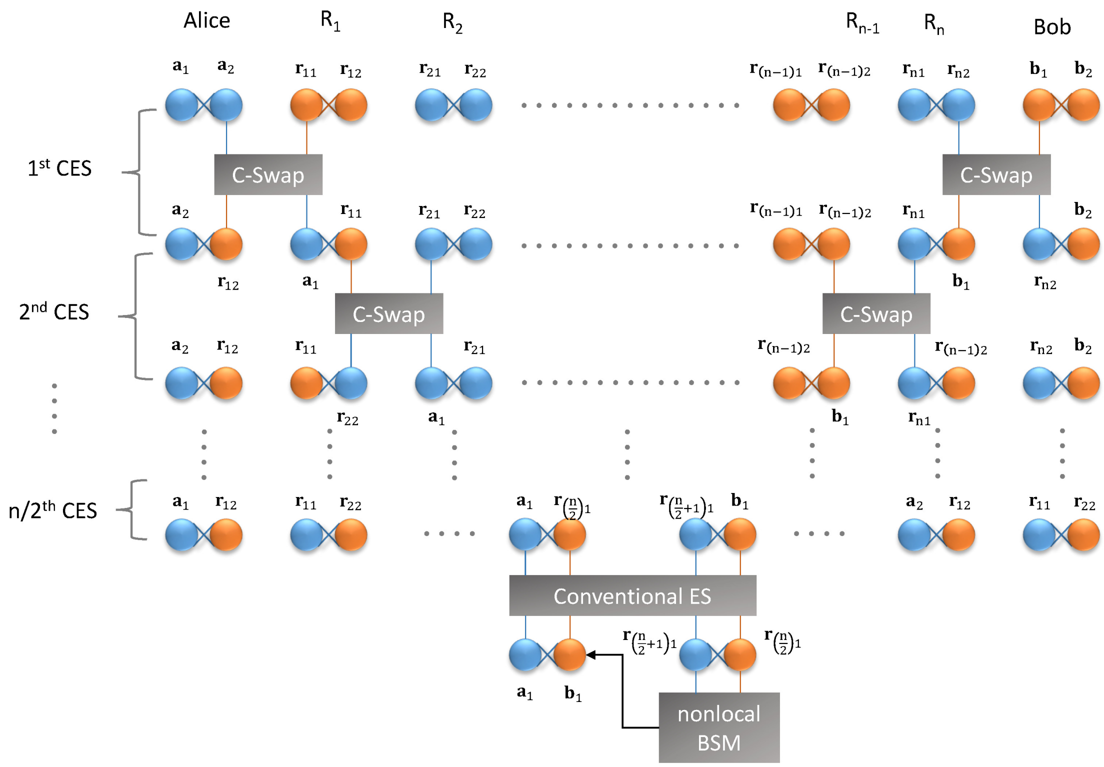


Fig. 4. Counterfactual long-distance quantum communication between two distant parties Alice and Bob, with n repeaters positioned as intermediary nodes between them. Alice and Bob hold QAO-QAO entangled pair and photon-photon entangled pair respectively. Even-numbered repeaters are equipped with photon-photon entangled pairs, while odd-numbered repeaters hold QAO-QAO pairs. Starting from the end nodes, counterfactual entanglement swapping is executed with their adjacent nodes until it the counterfactual entanglement pairs are established between Alice and $R_{\frac{n}{2}}$ and $R_{\frac{n}{2}+1}$ and Bob. Finally, conventional entanglement swapping with nonlocal Bell state measurement (BSM) is performed on them to establish entanglement between Alice and Bob, facilitating long-distance communication. Meanwhile, there are also redundant counterfactual entanglement links between adjacent nodes.

Note that in conventional entanglement swapping, a Bell state measurement (BSM) is performed on one of the resulting entangled pairs to determine the nature of entanglement present in the remaining pair. Thus, only one pair is usable for quantum information processing task. In contrast, our CES procedure does not require the BSM step, allowing the two resulting entangled pairs to be used for various purposes.

B. Proposed Scheme

In this article, we propose counterfactual long-distance quantum communication by utilizing CES operations and quantum repeaters. As shown in Fig. 4, Alice and Bob are separated by distance of miles apart where they prepare QAO-QAO entangled pair and photon-photon entangled pair respectively. To facilitate long-distance communication, n quantum repeaters are positioned between them where n is an even integer. In this scheme, odd-numbered repeaters are equipped with photon-photon entangled pairs while even-numbered repeaters are equipped with QAO-QAO entangled pairs. The initial state of the whole system can be represented as

$$|\zeta_0\rangle = |\eta_0\rangle_{\mathrm{a_1a_2}} |\phi\rangle_{\mathrm{r_{11}r_{12}}} |\phi\rangle_{\mathrm{r_{21}r_{22}}} \dots |\phi\rangle_{\mathrm{r_{(n-1)1}r_{(n-1)2}}} |\phi\rangle_{\mathrm{r_{n1}r_{n2}}} |\eta_1\rangle_{\mathrm{b_1b_2}} \tag{10}$$

with $\alpha = \beta = \gamma = \delta = \frac{1}{\sqrt{2}}$ and $|\phi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$. Here $\mathrm{r_{i1}r_{i2}}$ denotes the qubits of repeater R_i where $i \in \{1, 2, \dots, n\}$.

In the first stage, Alice and R_1 engage in CES, where Alice inputs her QAO $\mathrm{a_1}$, while R_1 inputs his photon $\mathrm{r_{11}}$ into the C-Swap gate. Simultaneously, R_n and Bob execute CES, with R_n providing his QAO $\mathrm{r_{n2}}$ and Bob throwing his photon $\mathrm{b_1}$ into the C-Swap gate. This transforms $|\zeta_0\rangle$ to

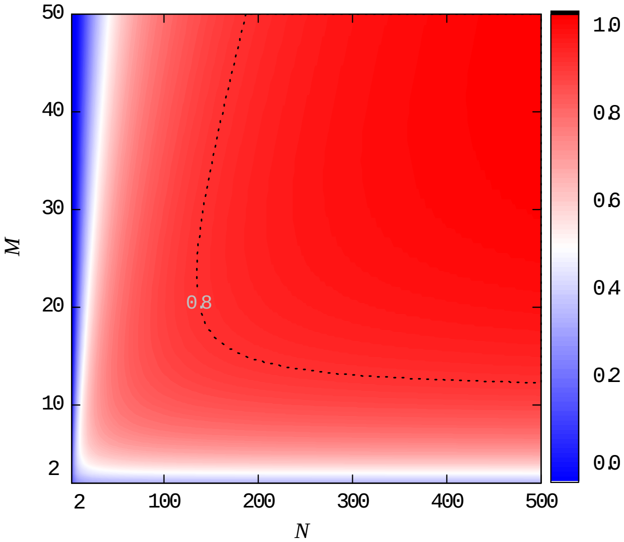
$$|\zeta_1\rangle = |\phi\rangle_{\mathrm{a_1r_{11}}} |\phi\rangle_{\mathrm{r_{21}r_{22}}} \dots |\phi\rangle_{\mathrm{r_{(n-1)1}r_{(n-1)2}}} |\phi\rangle_{\mathrm{r_{n1}b_1}} \left[|\phi\rangle_{\mathrm{a_2r_{12}}} |\phi\rangle_{\mathrm{r_{n2}b_2}}\right]. \tag{11}$$

Here, one of the entangled pairs from each CES operation is used for the subsequent CES operations while the remaining pairs serve as redundant communication link between adjacent nodes.

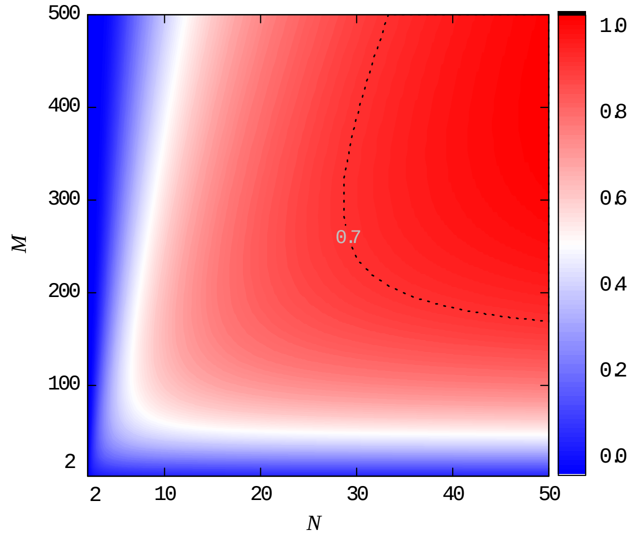
In the second stage, suppose that the entangled pairs $|\phi\rangle_{\mathrm{a_1r_{11}}}$ and $|\phi\rangle_{\mathrm{r_{n1}b_1}}$ are utilized for the CES operations with their neighboring repeaters R_2 and R_{n-1} respectively. The state of the system after the CES operations can be expressed as

$$|\zeta_1\rangle = |\phi\rangle_{\mathrm{a_1r_{21}}} \dots |\phi\rangle_{\mathrm{r_{(n-1)2}b_1}} \left[|\phi\rangle_{\mathrm{a_2r_{12}}} |\phi\rangle_{\mathrm{r_{11}r_{22}}} |\phi\rangle_{\mathrm{r_{(n-1)1}r_{n1}}} |\phi\rangle_{\mathrm{r_{n2}b_2}}\right]. \tag{12}$$

Since the objective is to establish counterfactual entanglement between two distant parties Alice and Bob, only entangled



(a) C-Swap gate



(b) Counterfactual long-distance quantum communication with 2 repeaters.

Fig. 5. The success probabilities of (a) C-Swap and (b) counterfactual long-distance quantum communication with 2 repeaters when $N = 500$ inner cycles and $M = R = 50$ outer cycles are used. As N and M increse, the success probabilities also increase.

pairs involving $|\phi\rangle_{\mathrm{a_1 r_{xy}}}$ and $|\phi\rangle_{\mathrm{r_{xy} b_2}}$ are exclusively employed among the four resulting entangled pairs for each subsequent stage of CES operations after the second stage, where $\mathrm{x} \in \{1, 2, \ldots, n\}$ and $\mathrm{y} \in \{1, 2\}$. With n repeaters, $n/2$ stages of CES operations are sequentially conducted between adjacent nodes until counterfactual entanglement is established between Alice and $R_{\frac{n}{2}}$ and between $R_{\frac{n}{2}+1}$ and Bob as follows

$$|\zeta_1\rangle = |\phi\rangle_{\mathrm{a_1 r_{(n/2)1}}} |\phi\rangle_{\mathrm{r_{(n+1/2)2} b_1}} \left[|\phi\rangle_{\mathrm{a_2 r_{12}}} |\phi\rangle_{\mathrm{r_{11} r_{22}}} \ldots |\phi\rangle_{\mathrm{r_{(n-1)1} r_{n1}}} |\phi\rangle_{\mathrm{r_{n2} b_2}}\right]. \quad (13)$$

The final entangled pairs $|\phi\rangle_{\mathrm{a_1 r_{(n/2)1}}}$ and $|\phi\rangle_{\mathrm{r_{(n+1/2)2} b_1}}$ undergo conventional entanglement swapping, incorporating a CCNOT gate. Instead of CNOT gate used in the BSM, we use CCNOT gate where nonlocal BSM can be performed between two remote parties in a particle-free manner. Here, the qubits $\mathrm{r_{(n/2)1}}$ and $\mathrm{r_{(n+1/2)2}}$ are subjected to a CCNOT gate. Subsequently, a Hadamard operation is performed on $\mathrm{r_{(n/2)1}}$ followed by a computational measurement on both qubits. Repeaters $R_{n/2}$ and $R_{n+1/2}$ communicate their respective measurement outcomes o_1 and o_2 through the classical authenticated channels. Each of these measurement outcomes has a uniform probability distribution, $P(o_i = 0) = P(o_i = 1) = \frac{1}{2}$, ensuring equal likelihood of both outcomes where $i \in \{1, 2\}$. Thus, eavesdroppers cannot gain useful information due to the uniformity and lack of correlation in the announced outcomes. Following this, Alice and Bob apply X^{o_1} and Z^{o_2} operations on their qubits respectively, establishing entanglement between them, $|\phi\rangle_{\mathrm{a_1 b_1}}$, without any information carrying particles passing through the channel.

IV. Results

For a given n repeaters, our proposed scheme requires $n/2$ stages of CES operations and a CCNOT operation. In each stage, there are two CES operations. Overall, the success probability of counterfactual long-distance quantum communication if no photon is lost to QAO can be calculated as

$$P = q^n p. \quad (14)$$

In Figure 5, we demonstrate the success probability of each CES operation and counterfactual long-distance quantum communication in the presence of $n = 2$ repeaters. In this scenario, we use $N = 500$ and $M = R = 50$ and access the success probability. It is obvious that as $N, M,$ and R increases, the success probability P approaches to unity.

V. Conclusion

We have introduced a new protocol for long-distance quantum communication, enabling primary communication link between two distant nodes as well as redundant communication links between neighboring nodes. Leveraging counterfactual communication, our approach enhances communication security, enabling secure information processing tasks across extended distances. Currently, achieving near-perfect success probabilities demands the utilization of large cycle numbers of $N, M,$ and R. As a future research direction, optimization techniques can be exploited to determine the minimum required number of of $N, M,$ and R based on the network configuration to realize the maximum efficiency for counterfacutal long-distance quantum-communication. Our proposed protocol serves as the foundation for realizing the full potential of counterfactual communication network in ensuring robust and secure long-distance information transmission.

Acknowledgment

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