# Quantum Teleportation over a Noisy Channel

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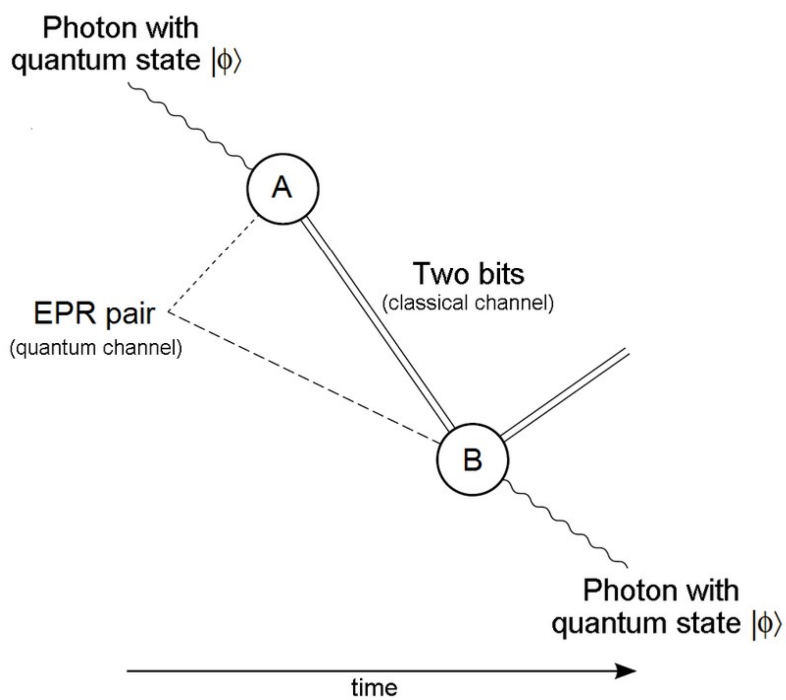
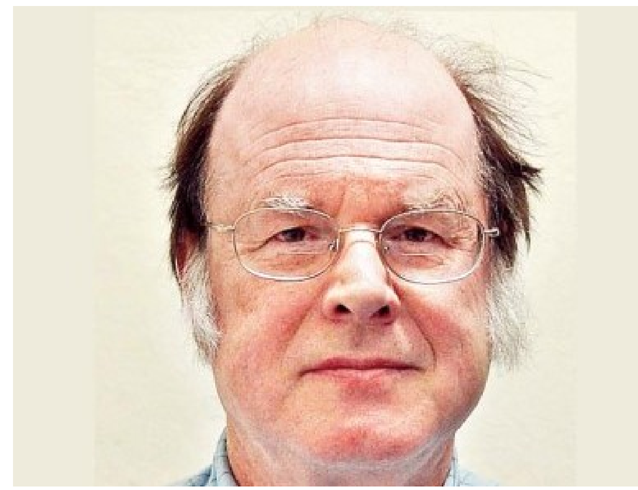
# Quantum Teleportation

A process in which quantum information (e.g. the exact state of an atom or photon) can be transmitted from one location to another, with the help of classical communication and previously shared quantum entanglement between the sending and receiving location.




The term was coined by physicist Charles Bennett [1].



[1] Bennett, C.H., Brassard, G., Crépeau, C., Jozsa, R., Peres, A.,Wootters,W.K.: Teleporting an unknown quantum state via dual classical and Einstein–Podolsky–Rosen channels. Phys. Rev. Lett. **70(13), 1895** (1993)

# Quantum Teleportation-Experimental demonstration

- In 1997, the first prosperous experimental demonstration of quantum teleportation was proposed by Bouwmeester [1] based on Benett et al. protocol.

**Dirk Bouwmeester**

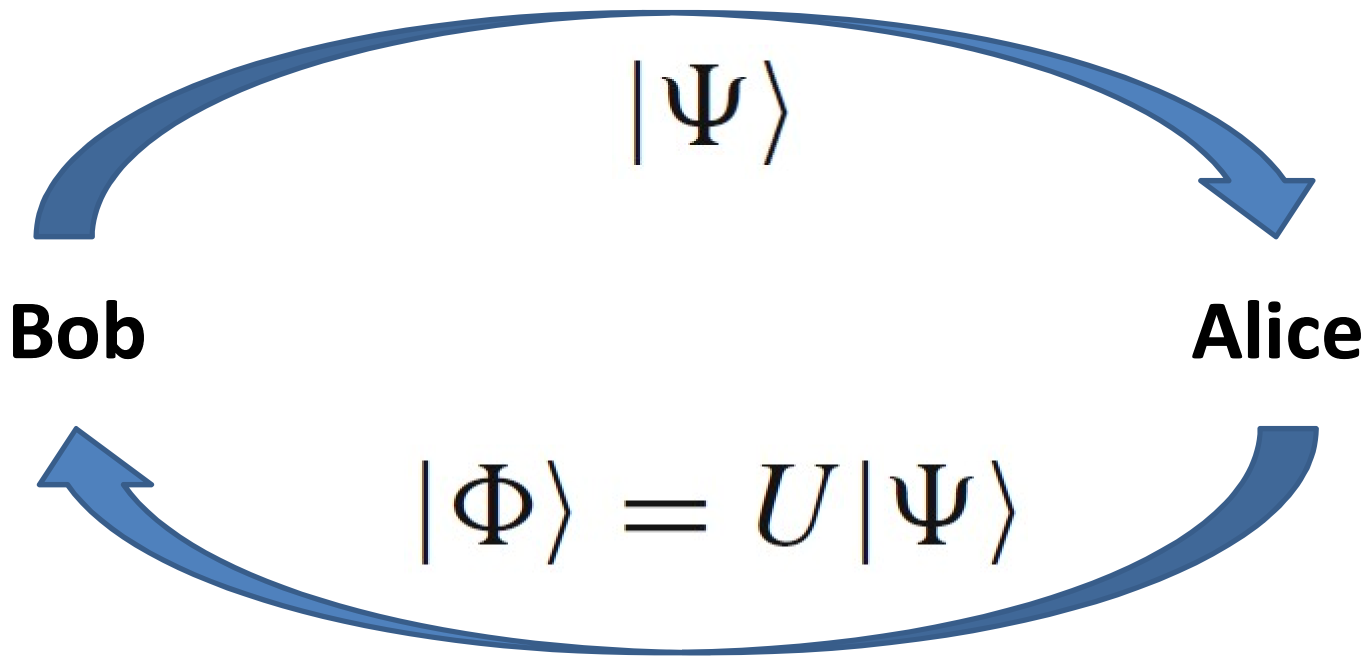
[1] Bouwmeester, D., Pan, J.-W., Mattle, K., Eibl,M.,Weinfurter, H., Zeilinger, A.: Experimental quantum teleportation. Nature **390(6660), 575–579 (1997)**

# Quantum Teleportation-Types

- quantum controlled teleportation (QCT)
- bidirectional quantum teleportation (BQT)
- bidirectional quantum controlled  teleportation (BQCT)
- multiparty-controlled teleportation (MCT)

# Bidirectional Quantum Teleportation (BQT)

- In a BQT scheme, Bob can teleport a quantum state to Alice, and then Alice applies a unitary operator *U on that and teleports back the state to Bob.*



# Bidirectional Quantum Teleportation (BQT)

- BQT can be used to implement a quantum remote control or a nonlocal quantum gate [1,2].
- The bidirectional state teleportation is an essential part of protocol design in cryptographic applications such as quantum key distribution (QKD) and quantum secret sharing (QSS) [3,4].

[1] Huelga, S.F., Plenio,M.B., Vaccaro, J.A.: Remote control of restricted sets of operations: teleportation of angles. Phys. Rev. A **65(4), 042316 (2002)**
[2] Thapliyal, K., Pathak, A.: Applications of quantum cryptographic switch: various tasks related to controlled quantum communication can be performed using bell states and permutation of particles. Quantum Inf. Process. **14(7), 2599–2616 (2015)**
[3] Deng, F.-G., Long, G.L.: Bidirectional quantum key distribution protocol with practical faint laser pulses. Phys. Rev. A **70(1), 012311 (2004)**
[4] Deng, F.-G., Zhou, H.-Y., Long, G.L.: Bidirectional quantum secret sharing and secret splitting with polarized single photons. Phys. Lett. A **337(4–6), 329–334 (2005)**

# Our proposed protocol

- Goal: Teleportation of arbitrary 2*n* *qubits* between Alice and Bob simultaneously [1]

(Published in Quantum Information Processing Journal in October 2019)

**[1] Sadeghi-Zadeh, M.S., Houshmand, M., Aghababa, H. et al. Quantum Inf Process (2019) 18: 353. https://doi.org/10.1007/s11128-019-2456-6**

# Our proposed protocol

- The states of Alice's and Bob's qubits are given in the following equations:

$$|\Phi\rangle_{A_1 A_2 \ldots A_n} = \sum_{i=0}^{2^n-1} \alpha_i |i\rangle,$$

$$|\Phi\rangle_{B_1 B_2 \ldots B_n} = \sum_{j=0}^{2^n-1} \beta_j |j\rangle,$$

**Where** $\sum_{i=1}^{n} |\alpha_i|^2 = \sum_{i=1}^{n} |\beta_i|^2 = 1$

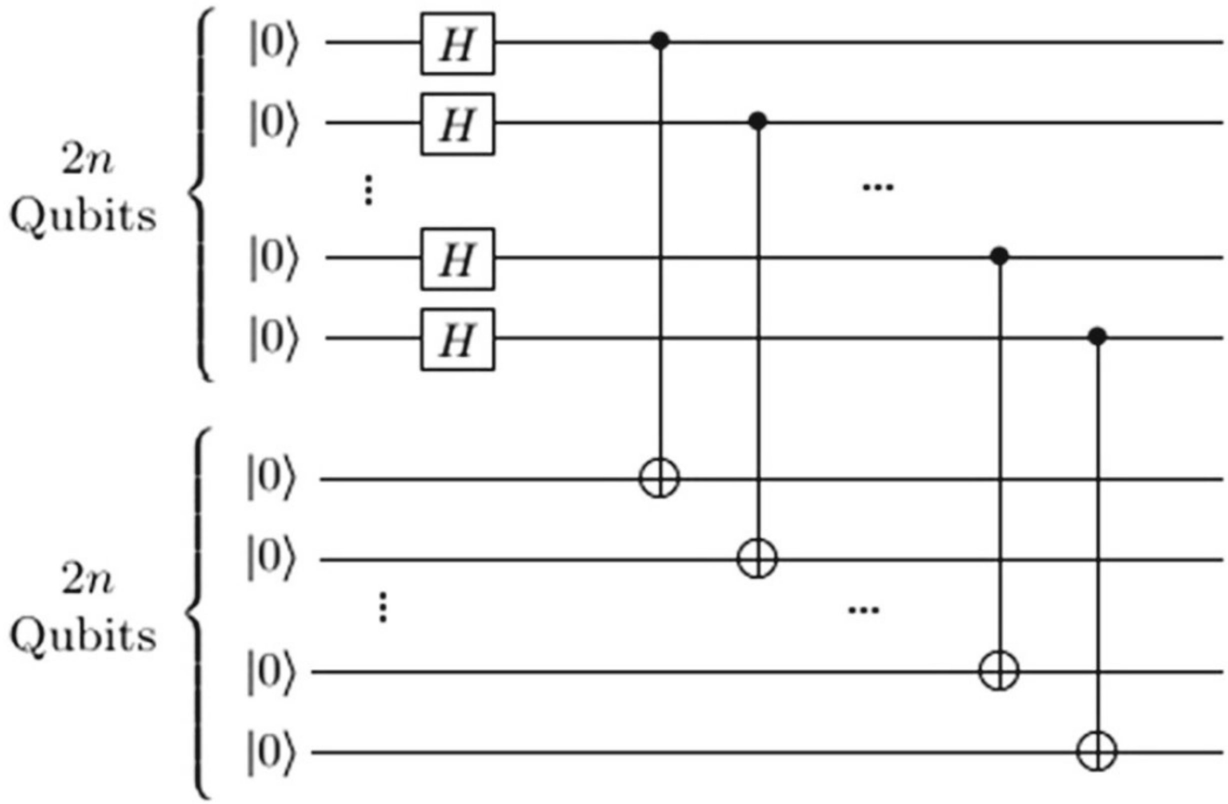
*i and j are decimal values of* $(i_1, \ldots, i_n)_2$ and $(j_1, \ldots, j_n)_2$

# Our proposed protocol

- The quantum channel of the proposed protocol is given in the following equation:

$$|G\rangle_{a_1 \ldots a_n b_1 \ldots b_n b_{n+1} \ldots b_{2n} a_{n+1} \ldots a_{2n}} = \frac{1}{2^{2n}} \sum_{l,k=0}^{2^n-1} |l\rangle|k\rangle|l\rangle|k\rangle.$$

# Our proposed protocol




**Architecture of the proposed 4*n-channel***

# Our proposed protocol

- Alice (Bob) receives the qubits $a_1 \ldots a_{2n}$($b_1 \ldots b_{2n}$) *from |G>.*
- The state of the whole 6*n-qubit quantum system* is given in the following equation:

$$|\Phi\rangle_{a_1 \ldots a_n b_1 \ldots b_n b_{n+1} \ldots b_{2n} a_{n+1} \ldots a_{2n} A_1 \ldots A_n B_1 \ldots B_n} = |G\rangle \otimes |\Phi\rangle_{A_1 \ldots A_n} \otimes |\Phi\rangle_{B_1 \ldots B_n}.$$

# Our proposed protocol

- The proposed protocol in five steps:

***Step 1: Alice (Bob) performs CNOT operators where $A_1A_2 \ldots A_n(B_1B_2 \ldots B_n)$ are*** **the control qubits and** ***$a_1a_2 \ldots a_n(b_1b_2 \ldots b_n)$ are the target qubits, respectively.*** **The state of the whole system after performing CNOT operators is given as follows:**

$$|\Phi\rangle_{A_1 \ldots A_n B_1 \ldots B_n a_1 \ldots a_n b_1 \ldots b_n b_{n+1} \ldots b_{2n} a_{n+1} \ldots a_{2n}}$$

$$= \frac{1}{2^{2n}} \sum_{i,j,k,l=0}^{2^n-1} \alpha_i \beta_j |i\rangle |j\rangle |l \oplus i\rangle |k \oplus j\rangle |l\rangle |k\rangle.$$

# Our proposed protocol

***Step 2: In this step, Alice and Bob measure qubits $a_1a_2 \ldots a_n$ and $b_1b_2 \ldots b_n$ in $Z$* basis, respectively. The results of this step are shown in Table 1.**

**Table 1** Measurement results of Step 2 and the corresponding applied operators in Step 3

| Alice's results | Bob's results | Collapsed states of qubits $A_1 \ldots A_n B_1 \ldots B_n b_{n+1} \ldots b_{2n} a_{n+1} a_{2n}$ | Operators by Bob applied on $b_{n+1} \ldots b_{2n}$ | Operators by Alice applied on $a_{n+1} \ldots a_{2n}$ |
|---|---|---|---|---|
| $0 \ldots 0$ | $0 \ldots 0$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle$ | $I^{\otimes n}$ | $I^{\otimes n}$ |
| $0 \ldots 0$ | $0 \ldots 01$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_{n-1} \bar{j}_n\rangle$ | $I^{\otimes n}$ | $I^{\otimes (n-1)} X$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $0 \ldots 0$ | $1 \ldots 11$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert i_1 \ldots i_n\rangle \lvert \bar{j}_1 \ldots \bar{j}_{n-1} \bar{j}_n\rangle$ | $I^{\otimes n}$ | $X^{\otimes n}$ |
| $0 \ldots 1$ | $0 \ldots 00$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert i_1 \ldots \bar{i}_n\rangle \lvert j_1 \ldots j_{n-1} j_n\rangle$ | $I^{\otimes (n-1)} X$ | $I^{\otimes (n)}$ |
| $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ | $\vdots$ |
| $1 \ldots 1$ | $1 \ldots 10$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert \bar{i}_1 \ldots \bar{i}_n\rangle \lvert \bar{j}_1 \ldots \bar{j}_{n-1} j_n\rangle$ | $X^{\otimes n}$ | $X^{\otimes (n-1)} I$ |
| $1 \ldots 1$ | $1 \ldots 1$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n \in \{0,1\}} \alpha_i \beta_j \lvert i_1 \ldots i_n\rangle \lvert j_1 \ldots j_n\rangle \lvert \bar{i}_1 \ldots \bar{i}_n\rangle \lvert \bar{j}_1 \ldots \bar{j}_{n-1} \bar{j}_n\rangle$ | $X^{\otimes n}$ | $X^{\otimes n}$ |

# Our proposed protocol

***Step 3: Alice and Bob apply X and I operators as shown in the fourth and fifth columns*** **of Table 1, respectively. All states result in the following equation:**

$$|\phi\rangle_{A_1 \ldots A_n B_1 \ldots B_n b_{n+1} \ldots b_{2n} a_{n+1} \ldots a_{2n}} = \frac{1}{2^{2n}} \sum_{i,j=0}^{2^n-1} \alpha_i \beta_j |i\rangle |j\rangle |i\rangle |j\rangle.$$

# Our proposed protocol

***Step 4: Alice and Bob perform X-basis measurement on $A_1 A_2 \ldots A_n$ and $B_1B_2 \ldots B_n$,* respectively. The measurement results and the corresponding states after the measurements are shown in Table 2.**

**Table 2** Measurement results of Step 4 and the corresponding applied operators in Step 5

| Alice's results | Bob's results | Collapsed states of qubits $b_{n+1} \ldots b_{2n} a_{n+1} \ldots a_{2n}$ | Operators by Bob applied on $b_{n+1} \ldots b_{2n}$ | Operators by Alice applied on $a_{n+1} \ldots a_{2n}$ |
|---|---|---|---|---|
| $+\cdots+$ | $+\cdots+$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} \alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $I^{\otimes n}$ | $I^{\otimes n}$ |
| $+\cdots+$ | $+\cdots+-$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} (-1)^{j_n}\alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $I^{\otimes n}$ | $I^{\otimes (n-1)}Z$ |
| $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ |
| $+\cdots+$ | $-\cdots-$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} (-1)^{\sum_{h=1}^{n} j_i}\alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $I^{\otimes n}$ | $Z^{\otimes n}$ |
| $+\cdots+-$ | $+\cdots+$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} (-1)^{i_n}\alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $I^{\otimes (n-1)}Z$ | $I^{\otimes n}$ |
| $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ | $\ldots$ |
| $-\cdots-$ | $-\cdots-+$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} (-1)^{\sum_{h=1}^{n} i_h+\sum_{h=1}^{n-1} j_h}\alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $Z^{\otimes n}$ | $Z^{\otimes (n-1)}I$ |
| $-\cdots-$ | $-\cdots-$ | $\sum_{i_1,\ldots,i_n,j_1,\ldots,j_n\in\{0,1\}} (-1)^{\sum_{h=1}^{n}(i_h+j_h)}\alpha_i\beta_j\|i_1\ldots i_n\rangle\|j_1\ldots j_n\rangle$ | $Z^{\otimes n}$ | $Z^{\otimes n}$ |

# Our proposed protocol

***Step 5: The last step of the proposed method focuses on correcting the collapsed states*** **by applying** ***Z operators as detailed in Table 2. After applying the mentioned Z operators, the state of whole system is as follows:***

$$|\phi\rangle_{b_{n+1}\ldots b_{2n}a_{n+1}\ldots a_{2n}} = \sum_{i,j=0}^{2^n-1} \alpha_i \beta_j |i\rangle |j\rangle.$$

# Our proposed protocol

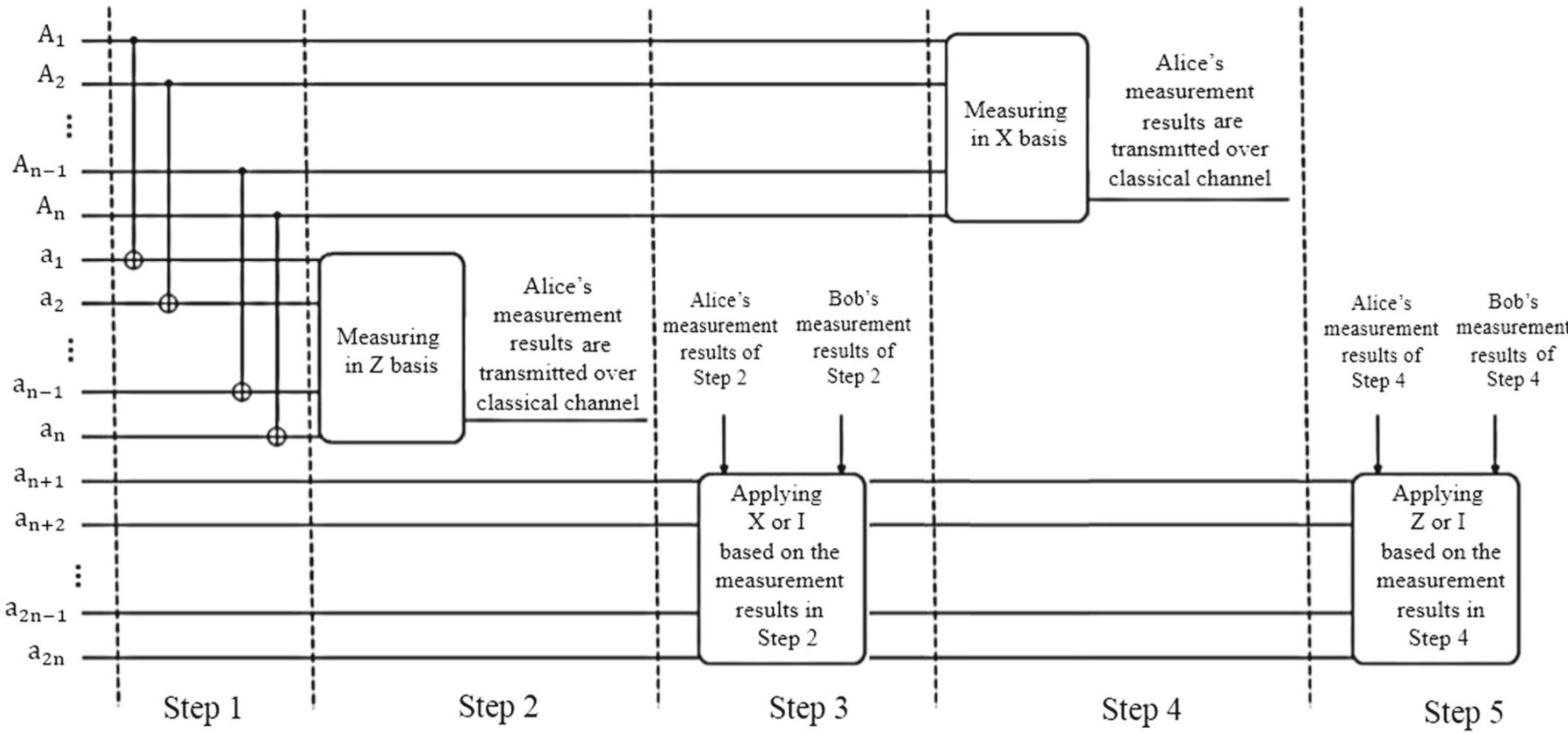
- Alice's and Bob's final states are shown in the following equations:

$$|\Phi\rangle_{a_{n+1}\ldots a_{2n}} = \sum_{i=0}^{2^n-1} \beta_i |i\rangle,$$

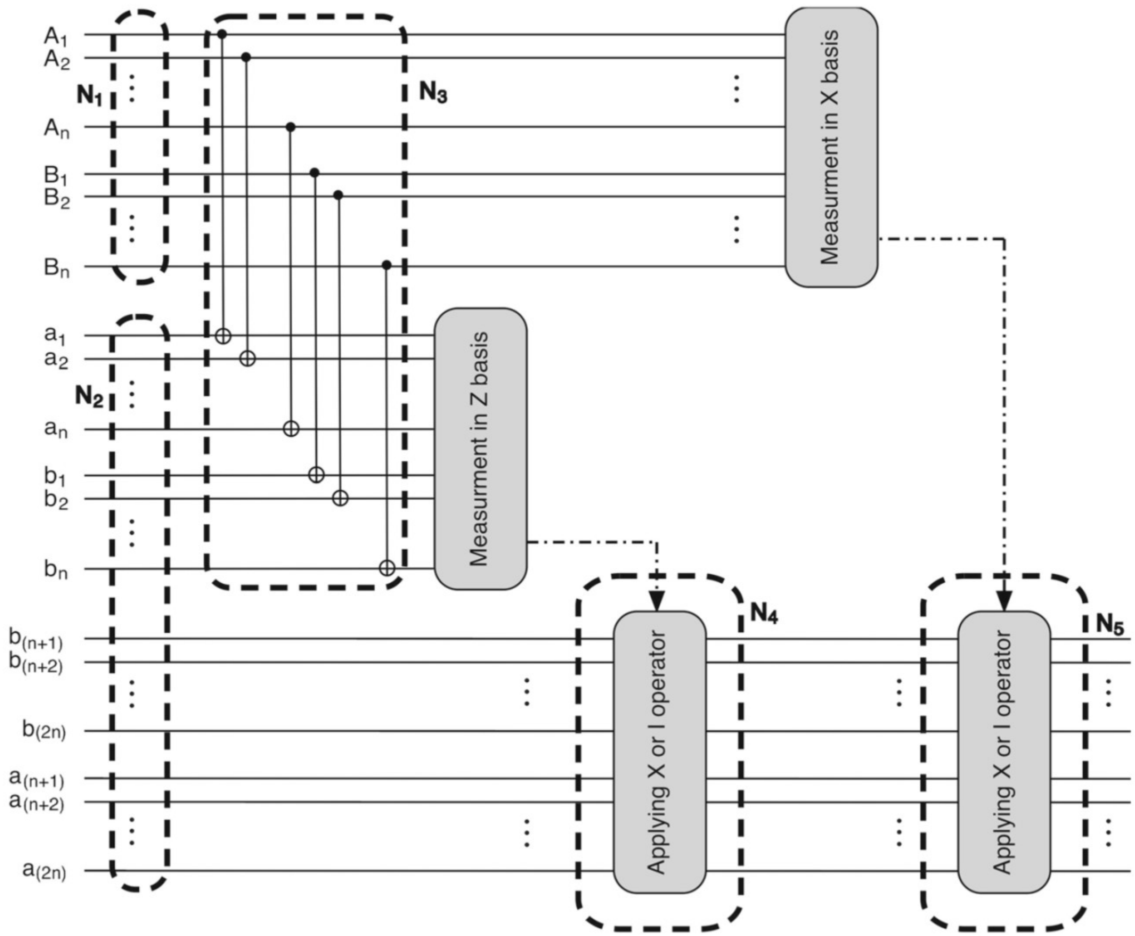
$$|\Phi\rangle_{b_{n+1}\ldots b_{2n}} = \sum_{i=0}^{2^n-1} \alpha_i |i\rangle.$$

# Our proposed protocol

**Architecture of the proposed protocol on Alice's side**



# Noise Analysis




**All parts which can be affected by noise in our quantum teleportation system**

# Noise Analysis

- In case *N1, our unknown input state loses its coherence* before it is teleported

- In case *N2, the entangled qubits make quantum channel* noisy while being shared and kept by Alice and Bob

- In cases *N3, N4 and N5, when* Alice and Bob perform the operations, the impact of noise may become notable

# Noise Analysis

- In this section, we investigate the effect of noise on input qubits (*N1) and channel* qubits (*N2), for some small case n = 1 and n = 2, considering the evolution of a* noisy system through a Markov evolution model

# Noise Analysis

- In our open quantum system after tracing out the environment degree of freedom, the dynamics of the density matrix of all our input and channel qubits can be described by a master equation in the Lindblad form [1],[2],[3]

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H_s, \rho] + \sum_{i,\alpha}\left( L_{i,\alpha}\, \rho\, L_{i,\alpha}{}^{\dagger} - \frac{1}{2}\left\{ L_{i,\alpha}{}^{\dagger} L_{i,\alpha}, \rho \right\} \right)$$


[1] Sangchul, O., Lee, S., Lee, H.: Fidelity of quantum teleportation through noisy channels. Phys. Rev.A **66(2), 022316 (2002)**

[2] Lindblad, G.: On the generators of quantum dynamical semigroups. Commun. Math. Phys. **48(2), 119–130 (1976)**

[3] Lidar, D.A., Chuang, I.L.,Whaley, K.B.: Decoherence-free subspaces for quantum computation. Phys.Rev. Lett. **81(12), 2594 (1998)**

# Noise Analysis

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H_s, \rho] + \sum_{i,\alpha}\left( L_{i,\alpha}\, \rho \;\; L_{i,\alpha}{}^{\dagger} - \frac{1}{2}\left\{ L_{i,\alpha}{}^{\dagger} L_{i,\alpha}, \rho \right\}\right)$$

$L_{i,\alpha} = \sqrt{\kappa_{i,\alpha}(t)}\,\sigma_{\alpha}^{(i)}$ $\Rightarrow$ Lindblad operator acts on the *ith qubits and describes* the decoherence

$\alpha = X, Y, Z$ $\Rightarrow$ stands for Pauli operations

$\kappa_{i,\alpha}$ $\Rightarrow$ the strength of the decoherence rates

$1/\kappa_{i,\alpha}$ $\Rightarrow$ the decoherence time (appriximately)

$$H_s\,(t) = -\frac{1}{2}\sum_{i=1}^{N} \mathbf{B}^{(i)}.\boldsymbol{\sigma}^{(i)} - \sum_{i \neq j} J_{ij}\,(t)\,\sigma_{+}^{(i)}\sigma_{-}^{(j)}$$

$\Rightarrow$ Hamiltonian of a qubit system

# Noise Analysis

$$H_s(t) = -\frac{1}{2}\sum_{i=1}^{N} \mathbf{B}^{(i)}.\boldsymbol{\sigma}^{(i)} - \sum_{i\neq j} J_{ij}(t)\,\sigma_+^{(i)}\sigma_-^{(j)}$$

Where $\boldsymbol{\sigma}^{(i)} = (\sigma_x^{(i)}, \sigma_y^{(i)}, \sigma_z^{(i)})$ & $\sigma_\pm^{(i)} = \frac{1}{2}(\sigma_x^{(i)} \pm i\sigma_y^{(i)})$

In solid-state qubits, various types of couplings between qubits *i and j are possible* such as *XY coupling given here*

The various quantum gates in our quantum teleportation system which exists in *N3, N4 and N5 noisy channel could be implemented by a sequence of* pulses, i.e., by turning on and off $B^{(i)}(t)$ and $J_{ij}(t)$ [1],[2]

[1] Sangchul, O., Lee, S., Lee, H.: Fidelity of quantum teleportation through noisy channels. Phys. Rev.A **66(2), 022316 (2002)**
[2] Makhlin, Y., Schön, G., Shnirman, A.: Quantum-state engineering with Josephson junction devices. Rev. Mod. Phys. **73, 357 (2001)**

# Noise Analysis

It is very useful to describe our quantum teleportation system in terms of density operators.

Hence, we can describe our teleportation system as follows:

$$\rho_{\mathrm{out}} = \mathrm{Tr}_{(a_{n+1}\hat{\ldots} a_{2n}) or (b_{n+1}\hat{\ldots} b_{2n})} \left[ U_{\mathrm{tel}} \left(\rho_{\mathrm{in}} \otimes \rho_{\mathrm{en}}\right) U_{\mathrm{tel}}^{\dagger} \right]$$

where

$$\rho_{\mathrm{in}} = |\Phi\rangle_{A_1\ldots A_n}\langle\Phi| \otimes |\Phi\rangle_{B_1\ldots B_n}\langle\Phi|$$

$$\rho_{\mathrm{en}} = |G\rangle_{a_1\ldots a_n b_1\ldots b_n b_{n+1}\ldots b_{2n} a_{n+1}\ldots a_{2n}}\langle G|$$

$\mathrm{Tr}_{(a_{n+1}\hat{\ldots} a_{2n})}$ $\Rightarrow$ partial trace over every qubits except $(a_{n+1} \ldots a_{2n})$

$U_{\mathrm{tel}}$ $\Rightarrow$ The unitary operator which is implemented by our teleportation circuit

# Noise Analysis

So, for investigating the noise effect on each channel *N1 or N2 with density matrix ρ, we analytically solve* Lindblad equation for *ρ and obtain the noisy density matrix ε(ρ) which is a function of* the state of our considered channel, *κ, t*

our noisy teleported qubits can be calculated as $\varepsilon(\rho_{out})$

we can quantify the properties of our quantum teleportation through noisy channels by computing fidelity between $\rho$ *and* $\varepsilon(\rho_{out})$ *which measures* the overlap between these two states as follows:

$$\text{Fidelity} = \langle\Phi|_{A_1\ldots A_n(or\,B_1\ldots B_n)}\varepsilon(\rho_{\text{out}})|\Phi\rangle_{A_1\ldots A_n(or\,B_1\ldots B_n)}$$

$\kappa t = 0$ ⟹ noise has not affected the system ⟹ Fidelity=1

# Noise Analysis

In order to measure the noise on input *(N1) and teleportation channel qubits (N2),* we should consider the value of Hamiltonian for *$t = 0$. In this case, the value of $H_s$* is zero

n=1 → An arbitrary state can be represented as a vector in a Bloch sphere:

$$|\Phi\rangle = \cos\left(\frac{\theta}{2}\right) e^{\frac{i\varphi}{2}}|0\rangle + \sin\left(\frac{\theta}{2}\right) e^{\frac{-i\varphi}{2}}|1\rangle$$

where *$\vartheta$ is the polar and $\varphi$ is the azimuthal angle*

The density matrix of the input qubits and that of the teleportation channel qubits are defined, respectively, as follows:

$$\rho_{\text{in}} = |\Phi\rangle_{A_1}\langle\Phi| \otimes |\Phi\rangle_{B_1}\langle\Phi|$$

$$\rho_{\text{en}} = |G\rangle_{a_1 b_1 b_2 a_2}\langle G|$$

# Noise Analysis

By solving the Lindblad equation for the noise of type *Z and X and for* $\rho_{in}$*, and* $\rho_{en}$*, the values of* $\varepsilon(\rho_{in})$*, and* $\varepsilon(\rho_{en})$ *are, respectively, calculated.*

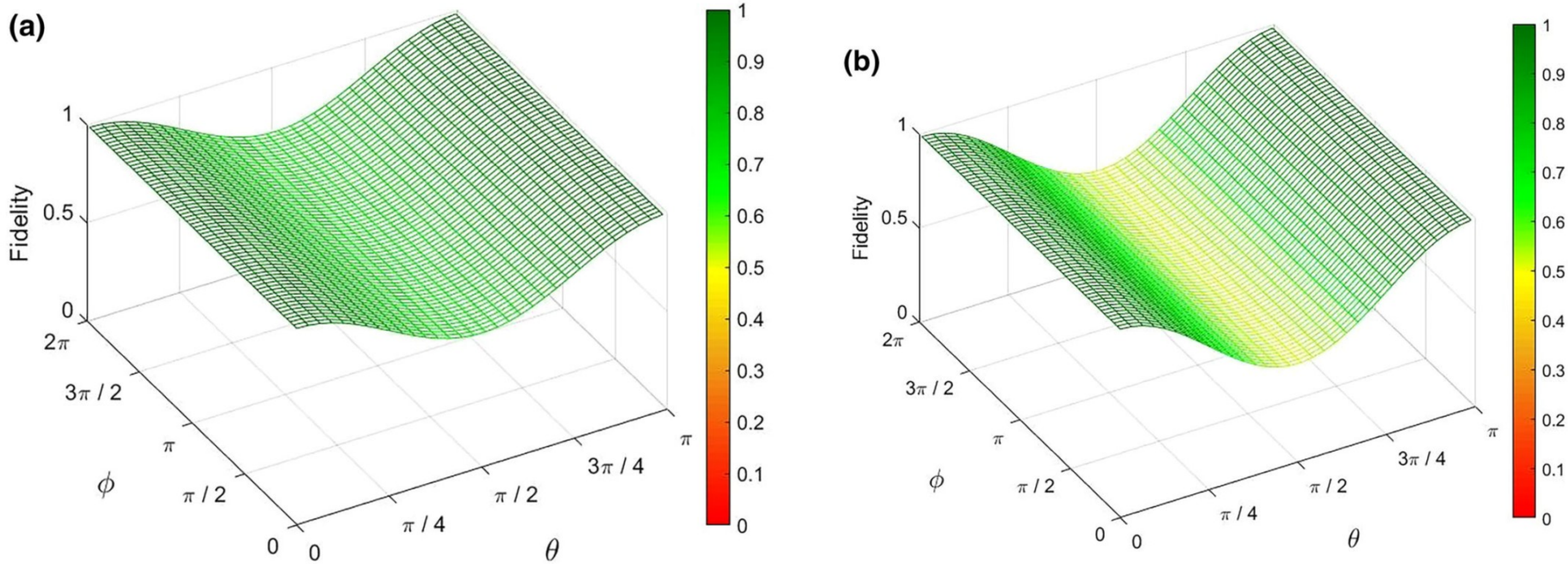
Additionally, for case *n = 1, the average of the fidelity can be* calculated as follows:

$$\text{Fidelity}_{\text{av}} = \frac{1}{4\pi} \int_0^{\pi} \mathrm{d}\theta \int_0^{2\pi} \mathrm{d}\phi \; \text{Fidelity} \; \times \; \sin(\theta)$$

# Noise Analysis

Fidelity of *Z noise on input qubits (N1) is as follows:*

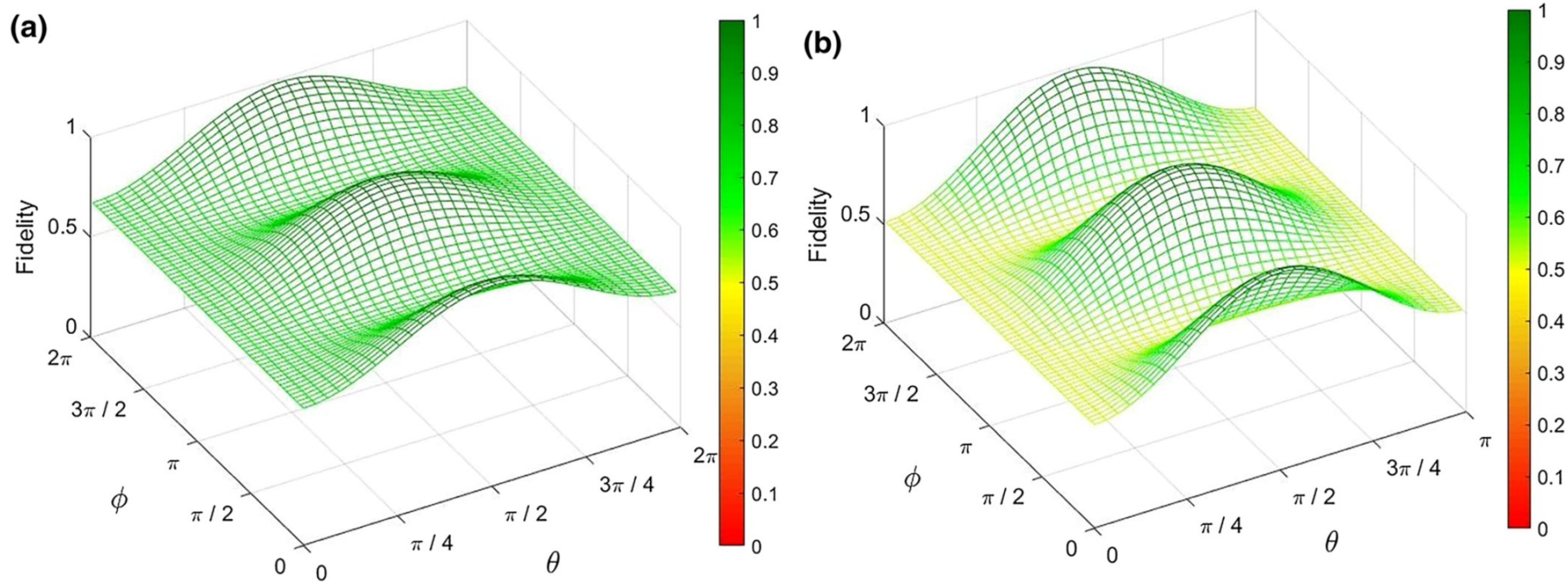
$$\text{Fidelity}\left(\theta_{A_1},\ \phi_{A_1},\ \kappa,\ t\right) = \frac{1}{4}\left[3 + \cos(2\theta_{A_1})\ +\ 2e^{-2\kappa t}\ \sin^2(\theta_{A_1})\right]$$




Fidelity of *Z noise. Minimum of **a** is 0.68, and minimum of **b** is 0.52. Maximum for both case is 1.* On input qubits (*$N_1$*): ***a** $\kappa t = 0.5$, **b** $\kappa t = 1.5$. On channel qubits ($N_2$): **a** $\kappa t = 0.25$, **b** $\kappa t = 0.75$*

# Noise Analysis

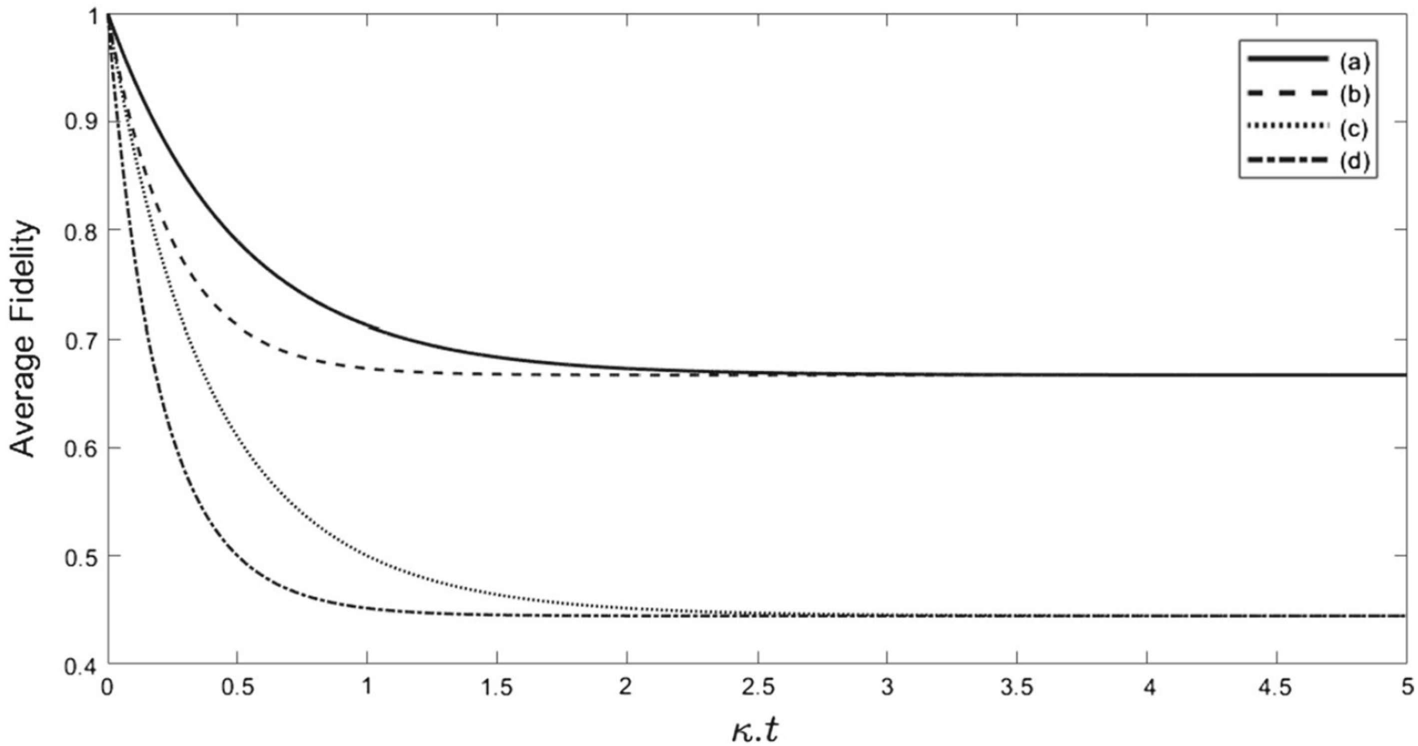
Fidelity of *X noise on input qubits (N1) is as follows:*




Fidelity of *X noise. Minimum of **a** is 0.68 and minimum of **b** is 0.52. Maximum for both cases is* 1. On input qubits (*N1): **a** κt = 0.5, **b** κt = 1.5. On channel qubits (N2): **a** κt = 0.25, **b** κt = 0.75*

# Noise Analysis

**As we previously explained, the average fidelity for *Z noise and X noise are* equal [1].**




**Average fidelity. a *n = 1, for input qubits (N1). b n = 1, for channel qubits (N2). c n = 2, for input* qubits (*N1). d n = 2, for channel qubits (N2)***

**[1] Sadeghi-Zadeh, M.S., Houshmand, M., Aghababa, H. et al. Quantum Inf Process (2019) 18: 353. https://doi.org/10.1007/s11128-019-2456-6**

# Comparison

| References | Year | Protocol type | Number of teleported qubits between Alice and Bob | Quantum channel |
|---|---|---|---|---|
| [19] | 2013 | BCQT | 1/1 | 5-qubit composite |
| [20] | 2014 | BQT | 1/1 | 4-qubit cluster |
| [24] | 2015 | BCQT | 1/1 | 6-qubit genuine |
| [21] | 2015 | BCQT | 1/1 | GHZ type |
| [13] | 2015 | BCQT | 1/1 | 8-qubit max Ent. |
| [22] | 2015 | BCQT | 1/1 | 6 qubit (3 Bells) |
| [35] | 2016 | BQT | 1/1 | 8 qubits |
| [40] | 2016 | BCQT | 1/2 | 7 qubits |
| [41] | 2016 | BCQT | 1/2 | 7 qubits |
| [23] | 2016 | BQT | 2(EPR)/2(EPR) | 6 qubits (2 GHZs) |
| [25] | 2016 | BCQT | 2/2 | 9-qubit cluster |
| [26] | 2016 | BCQT | 2/1 | 6-qubit cluster |
| [27] | 2017 | BQT | 2/2 | 8 qubits |
| Proposed protocol | 2017 | BQT | $n/n$ | $4n$ qubits |

# Our related works

[1] Sadeghi-Zadeh, M.S., Houshmand, M., Aghababa, H**.** et al. , "**Bidirectional quantum teleportation of an arbitrary number of qubits over noisy channel**," *Quantum Inf Process* 18: 353. https://doi.org/10.1007/s11128-019-2456-6 , **2019.**

[2] M. Sadeghizadeh, M. Houshmand, H. Aghababa, "**Bidirectional quantum teleportation of a class of n-qubit States by using (2n+2)-qubit**," *International Journal of Theoretical Physics,* DOI: 10.1007/s10773-017-3551-z, **2018***.*

[3] M. Sadeghizadeh, M. Houshmand, H. Aghababa, "**Bidirectional teleportation of a two-qubit State by using eight-qubit entangled state as a quantum channel**," *International Journal of Theoretical Physics*, DOI: 10.1007/s10773-017-3353-3, **2017**.


THANK YOU
FOR YOUR ATTENTION