Quantum Teleportation, Entanglement, and Bell Nonlocality in Unruh Channel

Soroush Haseli

Received: 27 October 2020 / Accepted: 16 January 2021 / Published online: 16 February 2021

Abstract
Decoherence is an unavoidable phenomenon that results from the interaction of the system with its surroundings. The study of decoherence due to the relativistic effects has the fundamental importance. The Unruh effect is observed by the relativistically accelerated observer. The unruh effect can be considered as a quantum channel called Unruh channel. The Unruh channel can be characterized by its Kraus representation. We consider the bipartite scheme in which the quantum information is shared between an inertial observer (Alice) and an accelerated observer (Rob) in the case of Dirac field. We will show that this channel reduces the common quantum information between the two observers. In this work we will study the effects of the Unruh channel on various facets of quantum correlations, such as the quantum teleportation, entanglement, and Bell inequality violations for a Dirac field mode.

Keywords Quantum teleportation · Entanglement · Bell nonlocality · Unruh channel

1 Introduction
Decoherence is an unavoidable phenomenon that results from the interaction of quantum system with its surroundings. Quantum correlations will decrease as the quantum system interacts with its surroundings. The study of the effects of ambiguity on quantum correlations has been the subject of much recent work. The study of decoherence due to the relativistic effects has the fundamental importance both from a fundamental perspective as well as to assist in future experiments involving a relativistic observers. The relativistic effect, which are called Unruh effect (Davies 1975; Unruh 1976; Crispino et al. 2008), states that from accelerating moving observer point of view the Minkowski vacuum appears as a hot gas emitting the radiation of the black-body at Unruh temperature

\[ \tau = \frac{\hbar a}{2\pi k_B c}, \]

where \( c \) is the speed of light in vacuum and \( k_B \) is Boltzmann’s constant and \( a \) is the acceleration of the observer. Unruh effect is calculated with an idealization where acceleration continues for infinite time. Of course, there have been some interesting studies exploring the finite acceleration aspects of Unruh effect (Bruschi et al. 2012). The role of interaction time of detectors with the quantum field on Unruh effect has also been studied (Hu et al. 2012; Fukuma et al. 2014). The Unruh effect creates a decoherence-like effect (Omkar et al. 2016). It reduces the quantum information shared between an inertial observer (Alice) and an accelerated observer (Rob) in the case of bosonic or Dirac field modes (Alsing and Milburn 2003; Richter and Omar 2015). The study of Unruh effect is part of efforts to understand the relativistic concepts of quantum information theory (Czachor 1997; Hosler and Kok 2013; Banerjee et al. 2015, 2016; Alok et al. 2016; Peres and Terno 2004). The Unruh channel has the particular importance from the quantum information theory perspective because it is conjugate degradable channel (Bradler et al. 2010). A channel is conjugate degradable when the environment can be simulated from the output of the channel. This feature of the Unruh channel makes it possible to calculate the classical and quantum capacity of the channel, as well as the exchange between these two
capacities for a number of scenarios (Bradler et al. 2009; Wilde et al. 2012). The most important step towards the experimental realization in the field of relativistic quantum information can be obtained through circuit quantum electrodynamics, using superconducting quantum interferometric devices (Nation et al. 2012). The concept of geometric phase can also be used to suggest a possible detection of Unruh temperature at sufficiently small accelerations that are experimentally available (Martinez et al. 2011). In this work, by providing a geometric characterization of the Unruh channel, we will study various types of quantum correlations, such as, Bell inequality violations, entanglement and teleportation under the effect of the Unruh channel. Things that have been done so far in the context of Unruh channel are consist of either the fermionic (Alsing et al. 2006) or bosonic (Fuentes-Schuller and Mann 2005) channels, depending on whether one is working with a Dirac or a scalar field, respectively. According to the finite occupation of the fermionic states, the finite-dimensional density matrices can be obtained which leads to closed-form expressions for quantum information quantity. So, the finite-dimensional fermionic Dirac field are more easily interpreted than the infinite-dimensional bosonic scalar field. This makes us eager to consider the behavior of various concepts of quantum information on the fermionic Unruh channel. In this work we will consider fermionic Unruh channel associated with Dirac field (Alsing et al. 2006). It is observed that in the fermionic channel the entanglement and teleportation fidelity degrades by increasing the acceleration. It is also observed that Bell inequality does not violate for large value of acceleration. The work is organized as follows. In Sect. 2, we review the notion of the Unruh effect for a two-mode fermionic system. In Sect. 3, we study the Unruh effect as a quantum noise channel. In Sect. 4, we review briefly the teleportation fidelity, concurrence, and Bell-CHSH inequality. In Sect. 5, we provide some examples to study the effect of Unruh channel on the teleportation fidelity, concurrence, and Bell-CHSH inequality. In Sect. 6, we summarize the main results of this paper.

2 Unruh Effect

The Unruh effect is particularly studied by exploring the Minkowski (flat) space-time in terms of Rindler coordinates. The space-time is divided into two disconnected region by Rindler transformation such that, an accelerated observer in one region is separated from the other region. Due to the fact that the limited field modes are not connected in these two different regions the quantum information of accelerated observer degrades and leads to thermal bath. As mentioned earlier, in this work we consider the fermionic field with few degree.

Let us consider the case in which the two observers Alice (A) and Bob (R) share a maximally entangled state of two Dirac field modes at Minkowski space-time. In addition, we assume that each observer is equipped with detectors that are sensitive only to their respective modes. So, the quantum field is in a state

\[
|\psi\rangle_{AR} = \frac{1}{\sqrt{2}} \left( |0\rangle_{J}M |0\rangle_{J}H + |1\rangle_{J}M |1\rangle_{J}H \right),
\]

(2)

where \(|0\rangle_{J}M\) and \(|1\rangle_{J}M\) are vacuum and excitation states of the mode \(j\) in Minkowski space. The state of Alice is created by the field mode \(s\) and she has been equipped with detector sensitive to mode \(s\) while Bob’s state is constructed by the field mode \(k\) and he has been equipped with detector sensitive to mode \(k\). When Bob moves with uniform acceleration \(a\), the states corresponding to field mode \(k\) must be redefined in Rindler bases in order to describe what Bob sees. Considering the provided formalism the Minkowski vacuum state converts to the Unruh mode, while the excited state is a product state. In terms of modes in different Rindler region I and II, this concept can be expressed as

\[
|0_{k}\rangle_{M} = \cos r |0_{j}\rangle_{I} |0_{J}\rangle_{II} + \sin r |1_{j}\rangle_{I} |1_{J}\rangle_{II},
\]

\[
|1_{k}\rangle_{M} = |1_{j}\rangle_{I} |0_{J}\rangle_{II},
\]

(3)

where \(\cos r = \frac{1}{\sqrt{1 + \frac{\omega}{c}a}}\) \(\omega\) is the Dirac particle frequency and \(c\) is the speed of light in vacuum. Also worth mentioning that \(a \in [0, \infty)\) and so we have \(\cos r \in [\frac{1}{\sqrt{2}}, 1]\). Using this formulation the maximally entangled state in Eq. (2) can be rewritten as

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left( |0_{j}\rangle_{M} (\cos r |0_{k}\rangle_{I} |0_{J}\rangle_{II}
\right.
\]

\[
+ \sin r |1_{j}\rangle_{I} |1_{J}\rangle_{II} + |1_{j}\rangle_{M} |1_{k}\rangle_{I} |0_{J}\rangle_{II} \right).
\]

(4)

Due to the fact that the two region I and II have no connection with each other in Rindler’s space-time, it is possible to take a partial trace over zone II and obtain the following density matrix

\[
\rho_{M} = \frac{1}{2} \left[ \cos^{2} r (|0_{j}\rangle_{M} |0_{k}\rangle_{I} |0_{J}\rangle_{II})
\right.
\]

\[
+ \cos r (|0_{j}\rangle_{M} |0_{k}\rangle_{I} |1_{J}\rangle_{II} + |1_{j}\rangle_{M} |1_{k}\rangle_{I} |0_{J}\rangle_{II})
\]

\[
+ \sin^{2} r (|0_{j}\rangle_{M} |1_{k}\rangle_{I} |0_{J}\rangle_{II} + |1_{j}\rangle_{M} |0_{k}\rangle_{I} |1_{J}\rangle_{II} \right].
\]

(5)

In the following we will discuss about the channel interpretation of the Unruh effect.
3 Characterization of Unruh Channel

In this section, Unruh channel is described from the insight of dynamical map in open quantum systems. Here, the Choi-Jamiolkowski isomorphism is used to define the Unruh channel. The Choi matrix corresponding to Unruh channel $\varepsilon_U$ can be derived by applying the Unruh channel on one half of a maximally entangled two-qubit state as

$$\rho_U = \begin{bmatrix} \cos^2 r & 0 & 0 & \cos r \\ 0 & \sin^2 r & 0 & 0 \\ 0 & 0 & 0 & 0 \\ \cos r & 0 & 0 & 1 \end{bmatrix},$$

(6)

The Kraus operators of the Unruh channel can be characterized by diagonalizing the Choi Matrix as (Usha Devi et al. 2011)

$$K_1 = \begin{bmatrix} \cos r \\ 0 \\ 0 \\ \sin r \end{bmatrix}, \quad K_2 = \begin{bmatrix} 0 \\ 0 \\ \sin r \\ 0 \end{bmatrix},$$

(7)

so, the Kraus representation of Unruh channel can be written as

$$\varepsilon_U (\rho) = \sum_{j=1,2} K_j \rho K_j^\dagger,$$

(8)

with the completeness condition

$$\sum_{j=1,2} K_j^\dagger K_j = I.$$  

(9)

Looking at the Kraus operators of Unruh channel, it can be seen that this channel is similar to the amplitude damping channel represents the effect of a zero temperature thermal bath (Nielsen and Chuang 2000; Banerjee and Ghosh 2007). However, Unruh effect is associated with a finite temperature, so it is logical to expect that the Unruh channel correspond to the generalized amplitude damping channels.

4 Teleportation, Entanglement, and Bell Nonlocality in Unruh Channel

In this paper, we consider the case in which inertial observer (Alice) wants to teleport to accelerated observer (Rob) the one-qubit state

$$|\psi_{in}\rangle = \cos(\theta/2)|0\rangle + e^{i\phi} \sin(\theta/2)|1\rangle,$$

(10)

where $\theta \in [0, \pi]$ and $\phi \in [0, 2\pi]$, while one can use a general two-qubit state $\rho$ as the quantum channel for teleportation. In a standard teleportation protocol in which the Rob is allowed to perform any unitary transformation, when reproducing the teleported state, the maximum average teleportation fidelity will be given by Horodecki et al. (1996)

$$F_{av}(\rho) = \frac{1}{2} + \frac{1}{6} N(\rho),$$

(11)

where $N(\rho) = tr \sqrt{T^\dagger T}$ and $T$ is a $3 \times 3$ positive matrix with the elements $T_{ij} = tr (\rho \sigma_i \otimes \sigma_j)$ where $\sigma_i$'s are Pauli matrices. In order to teleport $|\psi_{in}\rangle$ with higher fidelity than purely classical communication protocol, one requires the average fidelity is larger than 2/3.

Since the existence of entanglement between Alice and Rob is necessary for teleportation we consider the concurrence of $\rho$ as

$$C(\rho) = \max \{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\},$$

(12)

where $\lambda_i$'s are the eigenvalues of the Hermitian operator $\rho (\sigma_2 \otimes \sigma_2) \rho^* (\sigma_2 \otimes \sigma_2)$ arranged in non-increasing order and $\rho^*$ represents the complex conjugate of $\rho$. We will also study the Bell non-locality which is helpful to distinguish the two-qubit state $\rho$ enabling non-classical teleportation fidelity. For two-qubit states, the Bell non-locality can be detected by violation of the Bell-CHSH inequality (Clauser et al. 1969; Horodecki et al. 1996)

$$|\langle B_{\text{CHSH}} \rangle_{\rho}| = tr (\rho B_{\text{CHSH}}) \leq 2,$$

(13)

where $B_{\text{CHSH}}$ is the CHSH operator. The maximum of $|\langle B_{\text{CHSH}} \rangle_{\rho}|$ can be find as

$$B_{\text{max}}(\rho) = 2 \sqrt{u_1 + u_2},$$

(14)

where $u_1$ and $u_2$ are two largest eigenvalues of the $T^\dagger T$. The state $\rho$ is Bell non-local if $B_{\text{max}}(\rho) > 2$.

5 Examples

In this section we consider some examples to study the effect of Unruh channel on teleportation, entanglement, and Bell nonlocality. We will consider three different states with different features. Alice and Rob first share the states which has mentioned in the examples. Then let Rob move away from stationary Alice with a uniform proper acceleration $a$. Finally we study the teleportation, entanglement, and Bell nonlocality of transformed state.

5.1 Bell-Diagonal State

At first, we assume that Alice and Rob initially being at inertial frame and share a Bell-diagonal state of two Dirac field modes
\[ \rho^{AR} = \frac{1}{4} (I \otimes I + \sum_{i=1}^{3} r_i \sigma_i \otimes \sigma_i), \]  

where \( \sigma_i \) (\( i = 1, 2, 3 \)) are Pauli matrices. The above density matrix is positive if \( r = (r_1, r_2, r_3) \) belongs to a tetrahedron defined by the set of vertices \((-1, -1, -1), (1, 1, 1), (1, -1, 1) \) and \((1, 1, -1)\). Let us consider the case in which \( r_1 = 1 - 2p, r_2 = r_3 = -p \). So, the state in Eq. (15) can be rewritten as

\[ \rho^{AR} = p |\psi^-\rangle \langle \psi^-| + \frac{1-p}{2} (|\psi^+\rangle \langle \psi^+| + |\phi^+\rangle \langle \phi^+|), \]  

where \( |\phi^+\rangle = \frac{1}{\sqrt{2}}[|00\rangle \pm |11\rangle] \) and \( |\psi^+\rangle = \frac{1}{\sqrt{2}}[|01\rangle \pm |10\rangle] \) are the Bell diagonal states. Rob begins to move with an acceleration \( a \) while Alice stay in inertial frame. This is equivalent to the effect of Unruh channel on Rob’s state, so the transformed state can be obtained as

\[ \rho^{AI} = \sum_{i=1}^{2} (I \otimes K_i) \rho^{AR} (I \otimes K_i^\dagger). \]  

So, the maximum average teleportation fidelity is obtained as

\[ F_{av}(\rho^{AI}) = \frac{1}{2} + \frac{1}{6 \sqrt{2}} p^2 \cos^2 r \]
\[ + \frac{1}{12} \sqrt{\cos^2 r (1 - 3p - (1 - p) \cos r)^2} \]
\[ + \frac{1}{12} \sqrt{\cos^2 r (3p - 1 - (1 - p) \cos r)^2}. \]  

The concurrence can be obtained as

\[ C(\rho^{AI}) = 2 \max \{c_1, c_2\}, \]  

where

\[ c_1 = \frac{1}{4} \left| (1 - 3p) \cos r - \sqrt{(p - 1) \cos^2 r (p + 1) \cos 2r + p - 3} \right| \]
\[ c_2 = \frac{1}{4} \left| (p - 1) \cos^2 r - \sqrt{(p + 1) \cos^2 r (p - 1) \cos 2r + p + 3} \right|. \]  

In order to find the maximum of \( |\langle B_{\text{CHSH}} \rangle_{\rho^{AI}}| \) we have to find the eigenvalues of \( T^\dagger T \). These eigenvalues are

\[ u_1 = \frac{1}{4} \cos^2 r (p - 1) \cos r - 3p + 1)^2, \]
\[ u_2 = \frac{1}{4} \cos^2 r (p - 1) \cos r + 3p - 1)^2 \]
\[ u_3 = p^2 \cos^4 r. \]  

So, from Eq. (14) and considering the eigenvalues one can find the maximum of \( |\langle B_{\text{CHSH}} \rangle_{\rho^{AI}}| \) numerically.

In Fig. 1, we show \( F_{av}(\rho^{AI}), C(\rho^{AI}) \) and \( B_{\text{max}}(\rho^{AI}) \) versus probability parameter for different value of acceleration \( a \), when Alice and Rob initially share the Bell diagonal state. As can be seen from Fig. 1a, concurrence decreases with increasing the acceleration of Rob. Figure 1b shows that \( F_{av}(\rho^{AI}) \) decreases with increasing the acceleration of Rob. As can be seen in inertial frame \( a = 0 \) the teleportation fidelity is greater than 2/3 for all value of probability parameter while for the case in which Rob moves with acceleration \( a \) it is smaller than 2/3 for some values of probability parameter. So, one can conclude that for these values of \( p \) and \( a \) the states are not good enough to support quantum teleportation protocol. From Fig. 1c it can be seen \( B_{\text{max}}(\rho^{AI}) \) decreases with increasing acceleration. It is observed that the interval of \( p \) for which Bell-CHSH inequality is violated will be smaller with increasing acceleration.

### 5.2 Werner State

As a second example we consider the case in which Alice and Rob initially located in inertial frame and share a two-qubit Werner state of two Dirac field modes

\[ \rho^{AR} = \frac{1-p}{4} I \otimes I + p |\psi^-\rangle \langle \psi^-|, \]  

where \( 0 \leq p \leq 1 \). Rob begins to move with an acceleration \( a \) while Alice stay in inertial frame. This is equivalent to the effect of Unruh channel on Rob’s state, so the transformed state can be obtained as

\[ \rho^{AI} = \begin{pmatrix}
\frac{1-p}{4} \cos^2 r & 0 & 0 & 0 \\
0 & \frac{1-p}{4} \sin^2 r + \frac{1+p}{4} & -\frac{p}{2} \cos r & 0 \\
0 & -\frac{p}{2} \cos r & \frac{1+p}{4} \cos^2 r & 0 \\
0 & 0 & 0 & \frac{1+p}{4} \sin^2 r + \frac{1-p}{4}
\end{pmatrix}. \]  

The maximum average teleportation fidelity can be obtained as

\[ F_{av}(\rho^{AI}) = \frac{1}{2} + \frac{1}{6} p \cos^2 r \]
\[ + \frac{p}{3} \cos r. \]  

The concurrence becomes

\[ C(\rho) = 2 \max \{0, c_1\}, \]  

where

\[ c_1 = \left| -\frac{p}{2} \cos r - \sqrt{\frac{1-p}{4} \cos^2 r (\frac{1+p}{4} \sin^2 r + \frac{1-p}{4})} \right|. \]  

In order to obtain the maximum of \( |\langle B_{\text{CHSH}} \rangle_{\rho^{AI}}| \) we have to
find the eigenvalues of $T^\dagger T$. These eigenvalues can be obtained as
\begin{align}
  u_1 &= p^2 \cos^2 r, \\
  u_2 &= p^2 \cos^2 r, \\
  u_3 &= 2p^2 \cos^2 r.
\end{align}

So, from Eq. (14) and considering the eigenvalues one can find the maximum of $|B_{\text{CHSH}}|^2$ numerically.

In Fig. 2, $F_{\text{av}}(\rho^A)$, $C(\rho^A)$ and $B_{\text{max}}(\rho^A)$ are plotted in terms of probability parameter $p$ for different value of acceleration $a$, when Alice and Rob initially share a two-qubit Werner state. As can be seen from Fig. 2a, concurrence decreases with increasing the acceleration of Rob. Figure 2b shows that $F_{\text{av}}(\rho^A)$ decreases with increasing the acceleration of Rob. It is observed that for both moving and inertial frame, $F_{\text{av}}(\rho^A)$ is smaller than 2/3 for some values of probability parameter. So, one can conclude that for these values of $p$ and $a$ the states are not good enough to support quantum teleportation protocol. From Fig. 2c it can be seen $B_{\text{max}}(\rho^A)$ decreases with increasing acceleration. It is observed that the interval of $p$ for which Bell-CHSH inequality is violated will be smaller with increasing acceleration.

### 5.3 X-State

As an another example we consider the case in which Alice and Rob initially located in inertial frame and share a two-qubit X-state of two Dirac field modes
\begin{equation}
  \rho^{AR} = (1 - p)|\psi^+\rangle\langle \psi^+| + p|\psi^-\rangle\langle \psi^-|,
\end{equation}

where $0 \leq p \leq 1$. Rob begins to move with an acceleration $a$ while Alice stay in inertial frame. This is equivalent to the effect of Unruh channel on Rob’s state, so the transformed state can be obtained as
\begin{equation}
  \rho^A = \begin{pmatrix}
  \frac{1 - p}{2} \cos^2 r & 0 & 0 & \frac{1 - p}{2} \cos r \\
  0 & \frac{p}{2} + \frac{1 - p}{2} \sin^2 r & \frac{p}{2} \cos r & 0 \\
  0 & \frac{p}{2} \cos r & \frac{p}{2} \cos^2 r & 0 \\
  \frac{1 - p}{2} \cos r & 0 & 0 & \frac{1 - p}{2} + \frac{p}{2} \sin^2 r
\end{pmatrix}
\end{equation}

The maximum average teleportation fidelity can be obtained as
In this work, the tools in quantum information were used to describe the Unruh-effect. The Unruh effect was considered as a quantum dynamical map with ordinary Kraus representation. In this work we studied the effect of Unruh channel on various quantum correlation such as the quantum teleportation, entanglement, and Bell inequality violations for a Dirac field mode. We have shown that these correlations decrease with increasing observer acceleration in the moving frame. It has also shown that as a result of the Unruh effect, it is not possible to teleport optimally for some states.

6 Conclusion

In this work, the tools in quantum information were used to describe the Unruh-effect. The Unruh effect was considered as a quantum dynamical map with ordinary Kraus representation. In this work we studied the effect of Unruh channel on various quantum correlation such as the quantum teleportation, entanglement, and Bell inequality violations for a Dirac field mode. We have shown that these correlations decrease with increasing observer acceleration in the moving frame. It has also shown that as a result of the Unruh effect, it is not possible to teleport optimally for some states.

References

Alok AK, Banerjee S, Sankar SU (2016) Quantum correlations in terms of neutrino oscillation probabilities. Nucl Phys B 909:65
Alsing PM, Milburn GJ (2003) Teleportation with a uniformly accelerated partner. Phys Rev Lett 91:180404
Alsing PM, Fuentes-Schuller I, Mann RB, Tessier TE (2006) Entanglement of Dirac fields in noninertial frames. Phys Rev A 74:032326
Banerjee S, Ghosh R (2007) Dynamics of decoherence without dissipation in a squeezed thermal bath. J Phys A Math Theor 40:13735
Banerjee S, Alok AK, Srifikant R, Hiesmayr BC (2015) A quantum-information theoretic analysis of three-flavor neutrino oscillations. Eur Phys J C 75:487
Banerjee S, Alok AK, MacKenzie R (2016) Quantum Fisher and skew information for Unruh accelerated Dirac qubit. Eur Phys J Plus 131(5):129
Bradler K, Hayden P, Panangaden P (2009) Private information via the Unruh effect. JHEP 08:074
Bradler K, Dutil N, Hayden P, Muhammad A (2010) Conjugate degradability and the quantum capacity of cloning channels. J Math Phys 51:072201
Bruschi DE, Fuentes I, Louko J (2012) Voyage to Alpha Centauri: entanglement degradation of cavity modes due to motion. Phys Rev D 85:061701
Clauser JF, Horne MA, Shimony A, Holt RA (1969) Proposed experiment to test local hidden-variable theories. Phys Rev Lett 23:880
Crispino LCB, Higuchi A, Matsas GEA (2008) The Unruh effect and its applications. Rev Mod Phys 80:787
Czachor M (1997) Einstein–Podolsky–Rosen–Bohm experiment with relativistic massive particles. Phys Rev A 55:72.
Davies PCW (1975) Scalar production in Schwarzschild and Rindler metrics. J Phys A 8:609
Fuentes-Schuller I, Mann RB (2005) Alice falls into a black hole: entanglement in noninertial frames. Phys Rev Lett 95:120404
Fukuma M, Sugishita S, Sakatani Y (2014) Master equation for the Unruh–DeWitt detector and the universal relaxation time in de Sitter space. Phys Rev D 89:064024
Horodecki R, Horodecki P, Horodecki M (1995) Violating Bell inequality by mixed spin $\frac{1}{2}$ states: necessary and sufficient condition. Phys Lett A 200:340
Horodecki R, Horodecki M, Horodecki P (1996) Teleportation, Bell’s inequalities and inseparability. Phys Lett A 222:21
Hosler D, Kok P (2013) Parameter estimation using NOON states over a relativistic quantum channel. Phys Rev A 88:052112
Hu BL, Lin SY, Louko J (2012) Relativistic quantum information in detectors field interactions. Class Quantum Grav 29:224005
Martinez EM-, Fuentes I, Mann RB (2011) Using Berry’s phase to detect the Unruh effect at lower accelerations. Phys Rev Lett 1067:131301
Nation PD, Johansson JR, Blencowe MP, Nori F (2012) Colloquium: stimulating uncertainty—amplifying the quantum vacuum with superconducting circuits. Rev Mod Phys 84:1
Nielsen M, Chuang I (2000) Quantum computation and quantum information. Cambridge University Press, Cambridge
Omkar S, Banerjee S, Srikanth R, Alok AK (2016) The Unruh effect interpreted as a quantum noise channel. Quantum Inf Comput 16:0757
Peres A, Terno DR (2004) Quantum information and relativity theory. Rev Mod Phys 76:93
Richter B, Omar Y (2015) Degradation of entanglement between two accelerated parties: bell states under the Unruh effect. Phys Rev A 92:022334
Unruh WG (1976) Notes on black-hole evaporation. Phys Rev D 14:870
Usha Devi AR, Rajagopal AK, Sudha (2011) Open-system quantum dynamics with correlated initial states, not completely positive maps, and non-Markovianity. Phys Rev A 83:022109
Wilde MM, Hayden P, Guha S (2012) Quantum trade-off coding for bosonic communication. Phys Rev A 86:062306