Quantum Network via Partial Entangled State

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Abstract —In this article we designed a quantum network consists of four nodes using pairs of partial entangled state (Werner-state). The nodes of this network are connected via Dzyaloshiniskii-Moriya (DM) interaction. The entanglement is quantified between all different nodes using Wootters concurrence. It is shown that there is a maximum entangled state generated between two nodes which are connected indirectly. The degree of entanglement depends on the direction of switching the interaction.

Index Terms—Entanglement, quantum network, dzyaloshiniskii-Moriya (DM) interaction, Entangled State

I. Introduction

In the last few years, much attention have been paid to implement the quantum computer, based on the basic principles of quantum mechanics [1], [2]. Certain complex problems (large scale data, data search and natural's phenomenon's simulation) can be solved by the quantum computer exponentially faster than its classical computer [3]-[6].

The big challenge to build functional, scalable quantum computer is to generate multi-entangled particles quantum network) [7]. The coupling of an arbitrarily large number of qubits is needed to implement real quantum computer [8], [9], with the possibility to switch on and off the coupling by means of external control [10]. In principle, coupling of only nearest-neighbour qubits is sufficient to perform a universal set of gates [11].

Several proposals are suggested to implement the quantum computer. Solid state proposals show great promise for scalable quantum computer architecture. Two well-known proposals for quantum computation have been presented, including semiconducting quantum dots [12] and superconducting Josephson junctions [13]. Quantum dots currently enable the confinement and control of electrons on the scale of tens of nanometers. Spins in quantum dots can act as the qubit for quantum computation.

Dzyaloshiniskii–Moriya (DM) interaction is anisotropic antisymmetric exchange interaction resulting from the spins between neighbouring dots which plays an important role in the coupling among the macroscopic scale systems [14], [15]. The Dzyaloshiniskii–Moriya (DM) interaction is detected and characterized in the quantum dot systems [15] and in the weak ferromagnet [16] experimentally. It is well known that, the DM interaction in quantum information science is very useful [14], [15]. Much works have been done studying the importance of DM interaction in the process of quantum entanglement (short range entanglement) [17], [18]. For example, the dynamics of quantum discord and entanglement for two spin qubits coupled to a spin chain with Dzyaloshinsky-Moriya (DM) interaction is studied in [17]. Hou *et. al.* proposed theoretical scheme to preserve the entanglement in a two-qubit-spin coupled system in the presence of Dzyaloshinskii-Moriya (DM) interaction [19]. Percolation strategies based on multi-partite measurements to propagate entanglement in quantum networks using pure but non-maximally entangled pairs of qubits is presented [20]. The effect of Dzyaloshinskii-Moriya (DM) interaction on pairwise quantum discord, entanglement and classical correlation in the anisotropic XY spin-half chain is studied in ref. [21]. A good entanglement is generated between two distant atoms is connected by fiber optics by applying Lyapunov control [22]. Long-range entanglement is generated between the spin chains using the Local Rotational Protocols with spin chain [23]. Also, the information transmission by means quantum teleportation using spin chain in the presence of the DM interaction is investigated [24].

There are some efforts have been done to generate (multi-entangled particles) entangled networks via Dzyaloshiniskii-Moriya (DM) interaction. For example, Metwally 2011 has introduced theoretical scheme to generate quantum network using maximum entangled state (Bell State) via Dzyaloshiniskii-Moriya (DM) interaction [25]. The entanglement which generated between each two nodes is quantified. Morever the fidelity of the network channels to be used in the information exchange using the quantum teleportation is investigated. The entanglement is generated between different particles using Dzyaloshiniskii-Moriya (DM) interaction in the presence of spin-orbit coupling [26]-[28]. However from practical point of view, it is difficult to isolate the entangled network from its surrounding,

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therefore the decoharence takes place [29]-[32] and the maximum entangled states turn into partial entangled states. The purpose of this paper is to introduce theoretical technique to generate multi-participant's quantum network connected via partial entangled states of Werner type. The possibility of generation the entanglement among the network nodes using the DM-interaction in three directions (*x*, *y* and *z*) will be studied.

This paper is organized as follows: in Sec. II, the suggested system is described as well as an analytical solution is introduced. The entanglement between the different nodes is quantified in Sec. III. Finally our results are summarized in Sec. IV.

II. The Model

As we mentioned above, the main objective in this contribution is to generate an entangled network via partial entangled states. Figure (1) represents our suggested quantum network and we can see that node "1" and node "2" are initially generated as entangled particles as well as node "3" and node "4" (solid line). The dashed line represents that the entanglement between node "2" and "3" which is generated indirectly by the *DM* (M = *x*, *y* and *z*) interaction.

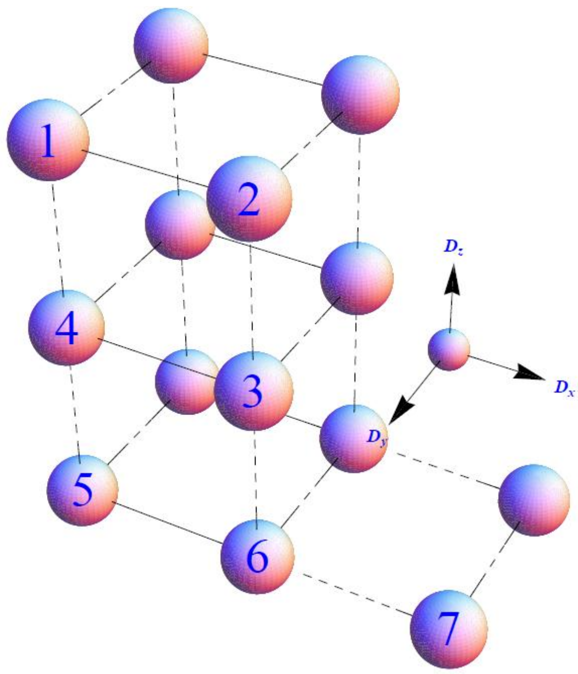

Fig. 1. Our suggested quantum network

We assume that we have a source supplies the users, who will be connected to the network with two qubit states of Werner types [33]. The density operator of these types of states is given by

$$\rho_{ij} = \frac{1-fw}{3} I_{4x4} - \frac{4fw-1}{3} |\Psi^{-}\rangle\langle\Psi^{-}| \tag{1}$$

where, ij=12, 34 and $|\Psi-\rangle = 1/\sqrt{2}(|00\rangle + |11\rangle$ is the Bell state and f_w is a constant in this paper we take the value of $fw = 1/\sqrt{2}$. To connect the nodes "2" and "3", we use DM interaction. The Hamiltonian of the DM interaction is defined by the following equation [15], [25].

$$\mathcal{H}_{DM} = D.(\sigma_i \times \tau_i) \tag{2}$$

where, $D = (D_x, D_y, D_z)$ is the coupling strength of the Dzyaloshiniskii-Moriya (DM) interaction and $\sigma_i = (\sigma_x, \sigma_y, \sigma_z)$ is Pauli operator for the first particle and $\tau_i = (\tau_x, \tau_y, \tau_z)$ is the Pauli operators for the second particle.

The initial system is described by $\rho_{1234}(0) = \rho_{12}(0) \otimes \rho_{34}(0)$. The time evolution of this initial state is given by

$$\rho_{1234}(t) = U_D(t)\rho_{1234}(0)U_D^{\dagger}(t) \tag{3}$$

where, U_D is a unitary operator and $U_D(t) = e^{-i\mathcal{H}_{DM}t}$and $U_D^{\dagger}(t)$ is the complex conjugate of $U_D(t)$

A. The Interaction is Awitched on X-axis

Let us assume that, the interaction is switched on x-axis and in our case the connection will be between the second and third qubit, respectively. In this case the unitary operator is defined by

$$U_{D_x}^{(23)}(t) = cos^2(2D_x t) + sin^2(D_x t)\sigma_x\tau_x - \frac{i}{2}\sin(2D_x\, t)(\tau_z\sigma_y - \tau_y\sigma_z) \tag{4}$$

In the computational basis (00, 01, 10 and 11), the unitary operator (4) can be written as

$$U_{D_x}^{(23)}(t) = \begin{pmatrix} u_{11,11} & u_{11,10} & u_{11,01} & u_{11,00} \\ u_{10,11} & u_{10,10} & u_{10,01} & u_{10,00} \\ u_{01,11} & u_{01,10} & u_{01,01} & u_{01,00} \\ u_{00,11} & u_{00,10} & u_{00,01} & u_{00,00} \end{pmatrix} \tag{5}$$

where $u_{00,00} = u_{01,01} = u_{10,10} = u_{11,11} = \cos^2 D_x(t)$, $u_{11,01} = u_{00,10} = u_{10,00} = u_{10,11} = -u_{01,00} = -u_{01,11} = -u_{11,01} = -u_{11,10} = i\, 2 \sin 2D_x(t)$ and $u_{00,11} = u_{01,10} = u_{10,01} = u_{11,00} = \sin^2 D_x(t)$.

By using Eq. (3) and Eq. (5), one obtains the time evaluation of the density operator $\rho_{1234}(t)$. From this density operator all the quantum channels between all nodes can be obtained. For example the density operator between the first, second node is given by,

The $\rho_{12x} = tr_{34}\{\rho_{1234x}(t)\}$ and between third fourth node by $\rho_{34x} = tr_{12}\{\rho_{1234x}(t)\}$

$$\rho_{12x} = \rho_{34x} = \frac{1}{4}(1 + C_{yy}^{(ij)}\sigma_y\tau_y) \tag{6}$$

where *ij* = 12*;* 34 represents the density matrix of the output channel when the interaction is switched on the *x*-direction, $C_{yy}^{(ij)} = -\sqrt{3}\, sin^2(D_x t)\sqrt{2}\, cos^2(D_x t) + sin(2D_x t)^2$. Similarly, the density matrix of node 1 and 3 is given by the following equation,

$$\rho_{13x} = (1 + C_{yz}^{(13)}\sigma_y\tau_z + C_{zy}^{(13)}\sigma_z\tau_y) \tag{7}$$

where $C_{yz}^{(13)} = -C_{zy}^{(13)} = \sqrt{2}i\, sin(2D_x t)$. In a similar way, the density operator between the first and the fourth node is:

$$\rho_{14x} = (1 + C_{xx}^{(14)}\sigma_x\tau_x + C_{yz}^{(14)}\sigma_y\tau_z + C_{zy}^{(14)}\sigma_z\tau_y) \tag{8}$$

where $C_{xx}^{(14)} = 1 - cos^2(Dxt) - sin^2(D_x t)$ and $C_{yz}^{(14)}\sigma_y\tau_z = -C_{zy}^{(14)}\sigma_z\tau_y = i\,sin(4D_x t)$. Finally, the density matrices of the channels $\rho_{23}(t)$ and $\rho_{24}(t)$ are given by

$$\rho_{ijx} = \frac{1}{4}\left(1 + S_z^i\sigma_z + t_z^j\tau_z + C_{zz}^{(ij)}\sigma_z\tau_z + C_{zy}^{(ij)}\sigma_z\tau_y\right) \quad (9)$$

with *ij* = 23*;* 24 represent the density matrix of the output channel when the interaction is switched in the *x*-direction with $S_z^i = t_z^i = C_{zz}^{(ij)} = 0.177\,cos(2Dxt) - \sqrt{2}sin(2Dxt)$ and $C_{zy}^{(ij)} = \sqrt{2}i\,sin(2Dxt)$

B. The Interaction is Awitched on Y-axis

Let us assume that, the interaction is switched on *y*-axis. In this case the unitary operator is defined by

$$\begin{aligned} U_{D_y}^{(23)} &= cos^2(2D_y t) + sin^2(D_y t)\sigma_y\tau_y \\ &\quad -\frac{i}{2}sin(2D_y\,t)(\tau_z\sigma_x - \tau_x\sigma_z) \end{aligned} \quad (10)$$

In the computational basis $U_{D_y}^{(23)}$ can be written as in eq. 5 Where $u_{00,00} = u_{01,01} = u_{10,10} = u_{11,11} = \cos^2 D_y(t)$, $u_{11,01} = -u_{00,10} = u_{10,00} = u_{10,11} = -u_{01,00} = -u_{01,11} = -u_{11,01} = u_{11,10} = i\,2\sin 2D_y(t)$ and $-u_{00,11} = u_{01,10} = u_{10,01} = -u_{11,00} = \sin^2 D_y(t)$

In a similar way, we can obtain the quantum states between all nodes. As an example, the quantum state between the first and the second nodes is given by,

The $\rho_{12y} = tr_{34}\{\rho_{1234y}(t)\}$ and between third fourth node by $\rho_{34y} = tr_{12}\{\rho_{1234y}(t)\}$.

$$\rho_{12x} = \rho_{34x} = \frac{1}{4}\left(1 + C_{xx}^{(ij)}\sigma_x\tau_x + C_{yy}^{(ij)}\sigma_y\tau_y + C_{zz}^{(ij)}\sigma_z\tau_z\right) \quad (11)$$

where ij=12, 34 and $C_{xx}^{(ij)} = -C_{zz}^{(ij)} = -\sqrt{2}i\,sin(2D_y t)$ and $C_{yy}^{(ij)} = -\frac{1}{\sqrt{2}}i\,sin(2D_y t)^2$. However in this case we found that the densities operator between the nodes 23 and 24 are similar i.e.,

$$\rho_{ijy} = \frac{1}{4}\left(1 + S_z^{(i)}\sigma_z + t_z^{(j)}\tau_z + C_{zz}^{(ij)}\sigma_z\tau_z + C_{yy}^{(ij)}\sigma_y\tau_y\right) \quad (12)$$

with *ij* = 23, 24 represent the density matrix of the output channel when the interaction is switched in the *y*-direction with $S_z^{(i)} = t_z^{(i)} = C_{zz}^{(ij)} = 0.177\,cos(2D_y t) - \sqrt{2}sin(2D_y t)$ and $C_{yy}^{(ij)} = \sqrt{2}i\,sin(2D_y t)^2$. Similarly the density operator between the nodes "1" and "3" are given by

$$\rho_{13y} = \frac{1}{4}\left(1 + C_{yy}^{(13)}\sigma_y\tau_y\right) \quad (13)$$

where $C_{yy}^{(ij)} = \sqrt{2}i\,sin(2D_y t)^2$

C. The Interaction is Awitched on Z-axis

In this case the unitary operator is given by

$$\begin{aligned} U_{Dz} &= cos^2(2D_z t) + sin^2(D_x t)\sigma_z\tau_z \\ &\quad -\frac{i}{2}\sin(2D_z\,t)(\tau_y\sigma_x - \tau_x y) \end{aligned} \quad (14)$$

In this case the unitary operator is given by

$$\mathcal{U}_{D_z}^{(23)}(t) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2D_z t & \sin 2D_z t & 0 \\ 0 & -\sin 2D_z t & \cos 2D_z t & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (15)$$

Similarly with previous sections, we can find the density operators between each two nodes. For example the density operator between the nodes 12 and 34 are given by,

$$\rho_{12z} = \rho_{34z} = \frac{1}{4}\left(1 + C_{xx}^{(ij)}\sigma_x\tau_x + C_{yy}^{(ij)}\sigma_y\tau_y + C_{zz}^{(ij)}\sigma_z\tau_z\right) \quad (16)$$

where *ij* = 12, 34 represents the density matrix of the output channel when the interaction is switched in the *z*-direction, with $C_{xx}^{(ij)} = C_{yy}^{(ij)} = -\sqrt{2}cos(2D_z t)$ and $C_{zz}^{(ij)} = -(1 + \frac{1}{\sqrt{2}}(sin(2D_z t)^2 - cos(2D_z t)^2))$. The density matrix of node 1 and 3 is given by,

$$\rho_{13z} = \left(1 + C_{xy}^{(13)}\sigma_x\tau_y + C_{yx}^{(13)}\sigma_y\tau_x\right) \quad (17)$$

where $-C_{xy}^{(13)} = C_{yx}^{(13)} = \sqrt{2}cos(2D_z t)$. Similarly, the density matrix of the node 1 and 4 is,

$$\rho_{14z} = \left(1 + C_{xy}^{(14)}\sigma_x\tau_y + C_{yx}^{(14)}\sigma_y\tau_x\right) \quad (18)$$

where $C_{xy}^{(14)} = -C_{yx}^{(14)} = \sqrt{2}\,sin(2D_z t)$. Finally, the density operators between the nodes 23, 24 are given by

$$\rho_{ijz} = \frac{1}{4}\left(1 + S_z^{(i)}\sigma_z + t_z^{(j)}\tau_z + C_{xy}^{(ij)}\sigma_x\tau_y + C_{yx}^{(ij)}\sigma_y\tau_x\right) \quad (19)$$

where $S_z^{(i)} + t_z^{(j)} = \frac{1}{\sqrt{2}}\,cos(2D_z t)^2$ and $C_{xy}^{(ij)} = C_{yx}^{(ij)} = \frac{\sqrt{2}}{2}sin(2D_z t)$

III. Results and Discussions

In this section, we use the concurrence as a measure of the degree of entanglement [34], [35]. For a two qubit system it is defined as

$$\mathcal{C} = max\{\sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}, 0\} \quad (17)$$

where λ_k, (k=1,2,3,4) is the eigenvalues of the matrix $\rho_{ij}(\sigma_y^{(i)} \otimes \sigma_y^{(j)})\rho_{ij}^*(\sigma_y^{(i)} \otimes \sigma_y^{(j)})$

Fig. 2 shows the dynamics of entanglement *C* between the nodes i and j for the entangled states $\rho_{ij} = 12{,}13$ and "14". The solid curve represents the dynamics of entanglement between the first node and the second node the dash curve between node "1" and node "3" and the dot dash curve between node "1" and node "4". In this figure the interaction is switched on the x-axis $D_x = 0.3$. It is shown that, the entanglement between the node "1" and "2" is started from a maximum value. This is because the initial state between node "1" and node "2" is partially entangled. As *t* increases, entanglement decreases and reaches its minimum value at *t* = 3 due to the interaction between the second node and third node. It is clear that, initially the nodes “1” and “3” are completely separable. Therefore, the entanglement between these two nodes at t = 0 is zero. However, as soon as the interaction is switched on, the two nodes turn into entangled. It is clear that, as t *increases* the degree of entanglement increases to reach its maximum value at t = 4. This behavior is repeated as one increase.

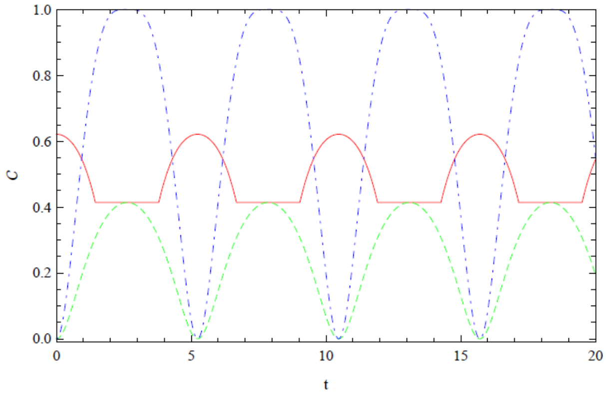

Fig. 2. The concurrence C_{ij} (ij = 12, 13 and 14) where the solid curve indicates to the entanglement between the first and second nodes, the dashed curve shows the entanglement between the first and the third node and the dot dashed curve shows the entanglement between the first and fourth nodes and the interaction is switched on the x-axis and D_x = 0.3

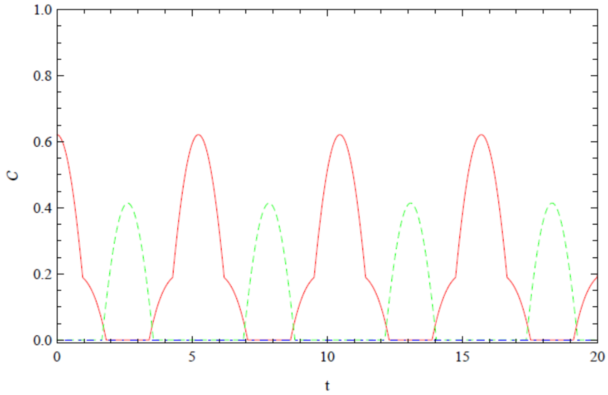

Fig. 3. The same with fig. (2) but when the interaction is switched on the y-axis and D_y = 0.3.

The entanglement between the first and (second, third and fourth nods), “12”, “13” and “14”, when the interaction is switched on y-direction is plotted in Fig. 3. From this figure we can see that, the entanglement between node “1” and “2” (solid curve) is initially started from the maximum value. This is in agreement with our argument that the first node and second node are started correlated. As time goes on the entanglement decreases and reaches zero around the scaled time of 2.

The entanglement remains equal to zero for some times after that when t = 4 the entanglement increases again in a periodical behavior. The entanglement between station “1” and “3” started form zero and remains zero tell t = 2 the entanglement start to increase and reach the maximum value C_{13} = 0.4 when t = 3. With increasing the time, the entanglement is decreases and reaches zero and remain equal zero for some times and start increasing again. The entanglement between station “1” and “4” is represented by the dash dot line in which we can see that there is no entanglement generated between these two nodes.

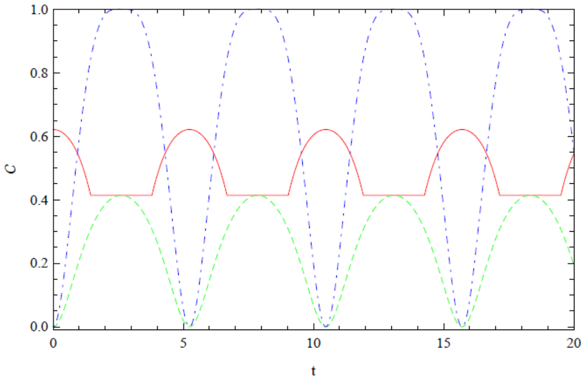

Fig. 4. The same with fig. (2) but the interaction is switched on the z-axis and D_z = 0.3.

Fig. 4 represents the dynamics of entanglement for states “12”, “13” and “14” when the interaction is switched in the z-direction. The figure shows that the entanglement over all channels is the same with Fig. 2 which represent the dynamics of entanglement over the same channels when the interaction is switched in the x-axis.

The entanglement dynamics over channels “34”, “23” and ”24” are plotted in the Fig. 5 when the interaction is switched on x-axis, where the solid line is the entanglement for channel "34" and dash line for channel “23” and dot dash curve is the entanglement for channel “24”. From the figure we can see that the entanglement between node “3” and node “4” started from the maximum value and with increasing of the time the entanglement decreased tell reach to 0.4 the entanglement take long-lived time the period from 1 to 4 which is completely the same with channel “12” because these two channels we proposed that were initially started entangled state.

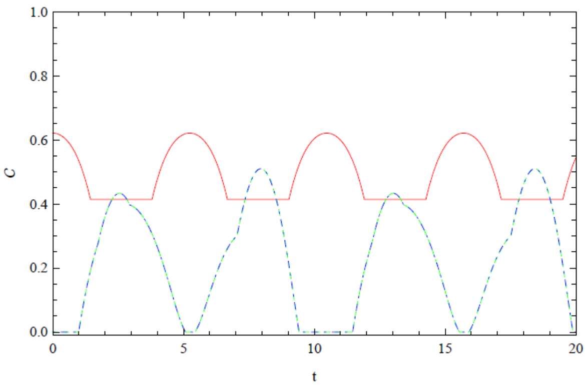

Fig. 5. The concurrence C_{ij} where ij= ”34”, ”23” and ”24” where the solid line is the entanglement between node "3" and "4" and dashed line represents the entanglement between node "2" and "3" and dot dashed line the entanglement between node "2" and "4" when the interaction is switched on the x-axis and D_x = 0.3.

From this figure we can see that the dynamics of the entanglement over channel “23” and “24” is the same where the it is started $C_{23,24}$ = 0 at time =0 and with the time increasing the entanglement increased and reach the maximum value $C_{23,24}$ = 0.43 at t = 2.5 and periodically repeated. Fig. 6 and Fig. 7 are the same as Fig. 5 but when the interaction is switched on y-axis and z-axis respectively.

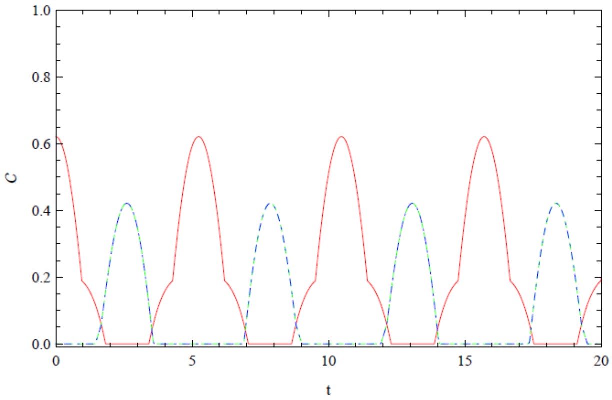

Fig. 6. The same with Fig. (5) but the interaction is switched on the y-axis and Dy = 0:3

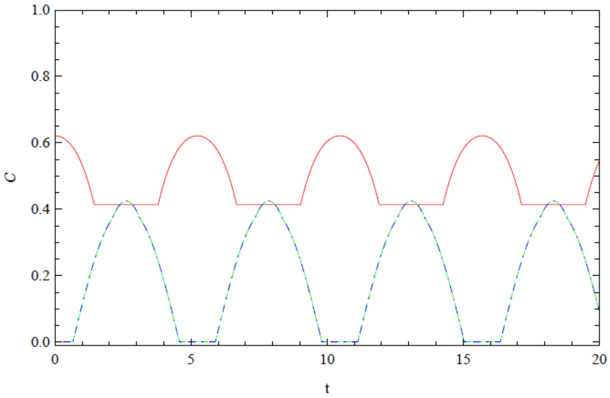

Fig. 7. The same with Fig. (5) but the interaction is switched on the z-axis and Dz = 0:3

IV. Conclusions

In this contribution, we suggest a simple model of quantum network, where each two nodes share a partially entangled state of Werner type. The disconnected nodes are connected via Dzyaloshiniskii-Moriya (DM) interaction, where we assume that DM is switch on all the possible directions. The degree of entanglement is quantified between all different nodes. Our results show that, there are entangled states are generated between all the disconnected nodes. The degree of entanglement depends on the location of the node. It is shown that, one can generate a long lived entanglement between these nodes when DM is switched on z or x directions. On the other hand, switching DM in y-direction preserve the entanglement between the nodes which are connected directly as well as that are connected indirectly. It is clear that the maximum entangled state doesn't exceed its initial value and the entanglement of the generated nodes that are connected indirectly always smaller than those are shared initially entangled state.

Finally, it is possible to generate entangled channels with maximum entanglement by controlling the direction of DM. Therefore, we can generate a maximum entangled network with high degree of entanglement; even we if we start from non-maximum entangled states.

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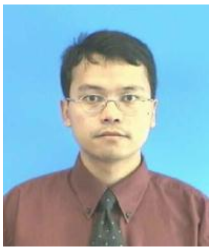

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