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Synchronization transition of a modular neural network containing subnetworks of different scales

Key words: Hodgkin–Huxley neuron; Modular neural network; Subnetwork; Synchronization; Transmission delay

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Motivation

- In neural networks, synchronization is an important spatio-temporal pattern that plays an important role in the realization of brain functions.
- Time delays are prevalent in the information transfer process of neural networks and are considered to be an important factor affecting the synchronization of the network.
- Most of the complex networks in the brain are modular, and studying the effect of time delays at different locations in modular neural networks (MNNs) on the synchronization of the networks has important implications for our understanding of brain functions.

Main idea

- A modular neural network (MNN) containing subnetworks of different scales is constructed.
- The synchronization of the networks is measured by a statistic synchronization factor R based on mean-field theory.
- We study the effect of time delays and coupling strengths on the synchronization of networks when the time delays are all the same in MNN.
- We study the effect of time delays at different locations in MNN on the synchronization of networks, and illustrate the mechanism of synchronization transition of the network through the statistic phase difference.

Network architecture

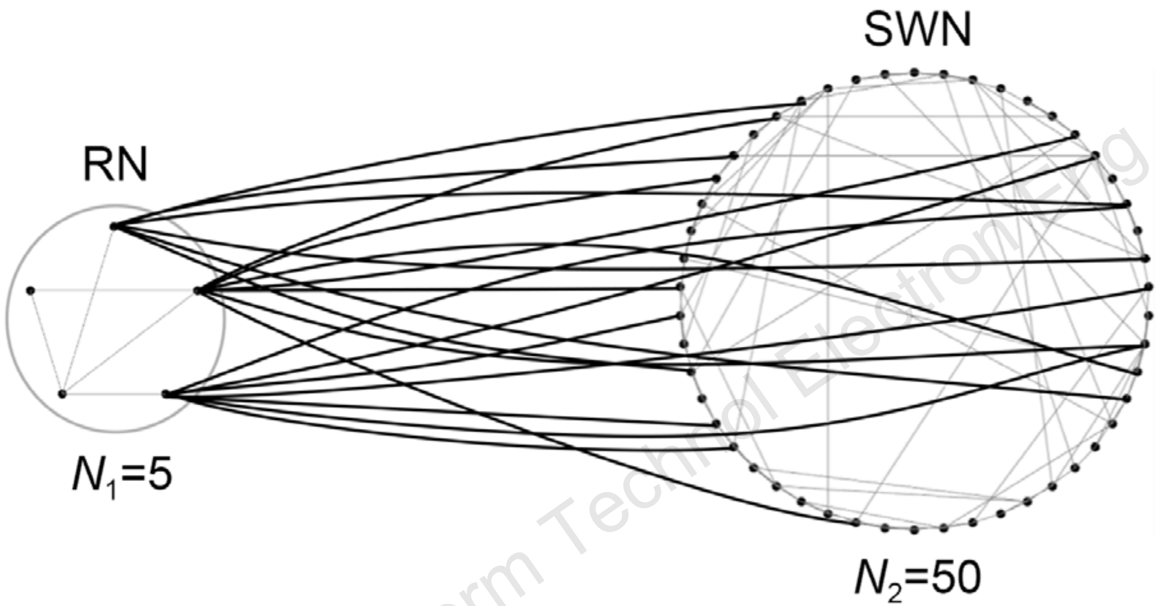

Fig. 1 Schematic of the modular neural network (RN: random network; SWN: small-world network)

The small-scale input network is a random network containing 5 neurons, and the large-scale receiver network is a small-world network containing 50 neurons. The two subnetworks are connected unidirectionally via chemical synapses with a connection probability of p=0.3.

Effect of time delay on the synchronization of networks

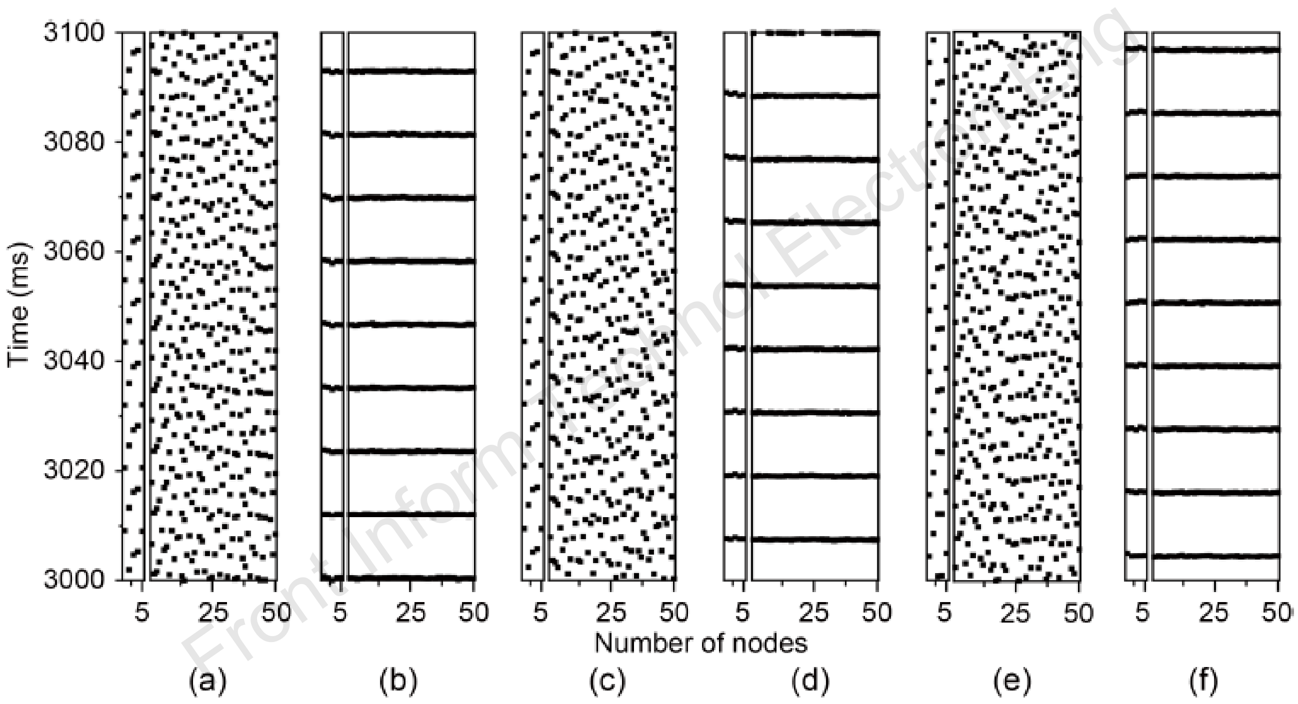

Fig. 2 Spatial-temporal firing raster plots of neural membrane potentials of the modular neural network (MNN) with different time delays τ (ms): (a) τ=5; (b) τ=10; (c) τ=16; (d) τ=21.5; (e) τ=27; (f) τ=33 (g=0.1 and D=0.1)

Effect of time delay and coupling strength on the synchronization of networks

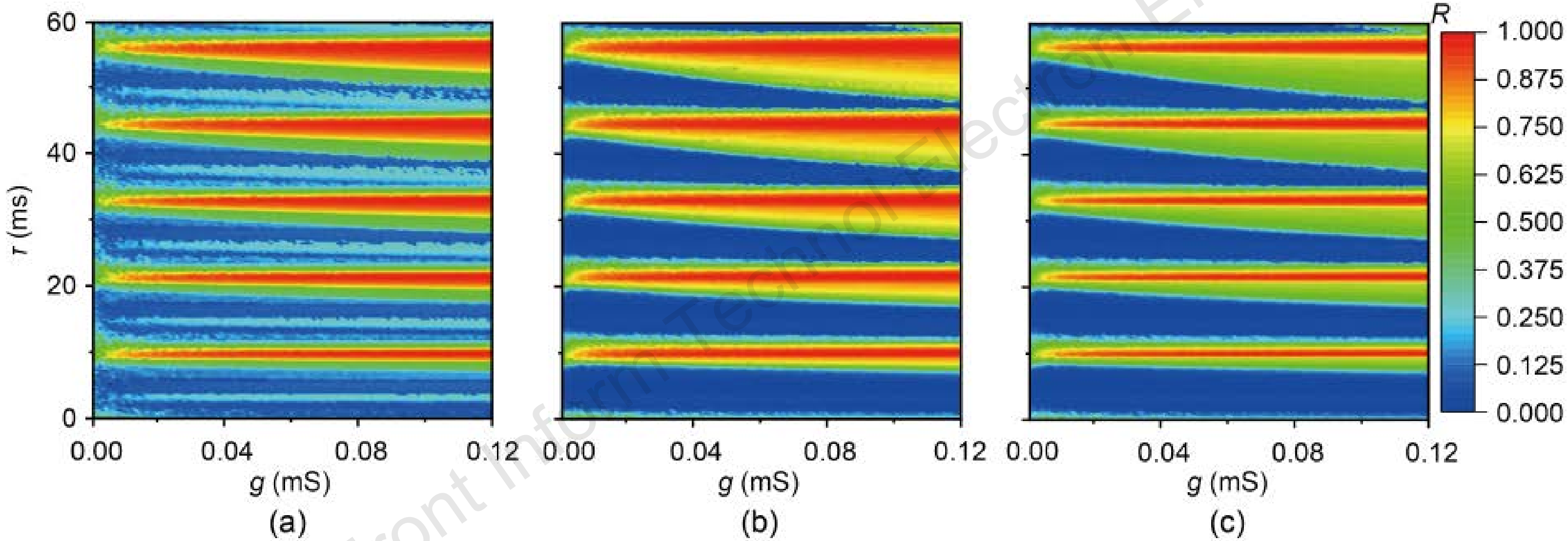

Fig. 5 Two-parameter diagram of the synchronization factor with respect to the coupling strength g and time delay τ: (a) random network (RN); (b) small-world network (SWN); (c) modular neural network (MNN) (D=0.1)

Effect of time delay within a small-scale subnetwork on the synchronization of MNN

- τ_1 represents the time delay between neurons within a small-scale subnetwork.

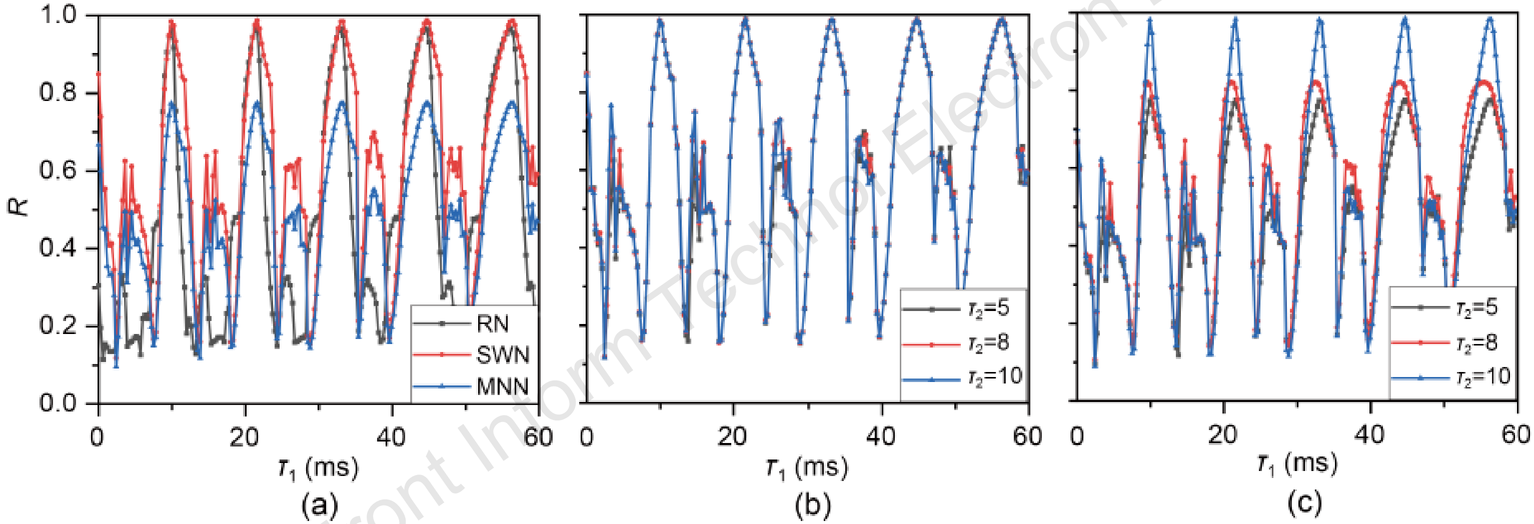

Fig. 10 Distribution of the synchronization factors in networks with increasing time delay τ_1: (a) distribution of the synchronization factors of the three networks when τ_2=5; (b) variation of the synchronization factors of the small-world network (SWN) when τ_2 is different; (c) variation of the synchronization factors of the modular neural network (MNN) when τ_2 is different (τ_3=10, g=0.1, and D=0.1)

Effect of time delay within a large-scale subnetwork on the synchronization of MNN

- τ_3 represents the time delay between neurons within a large-scale subnetwork.

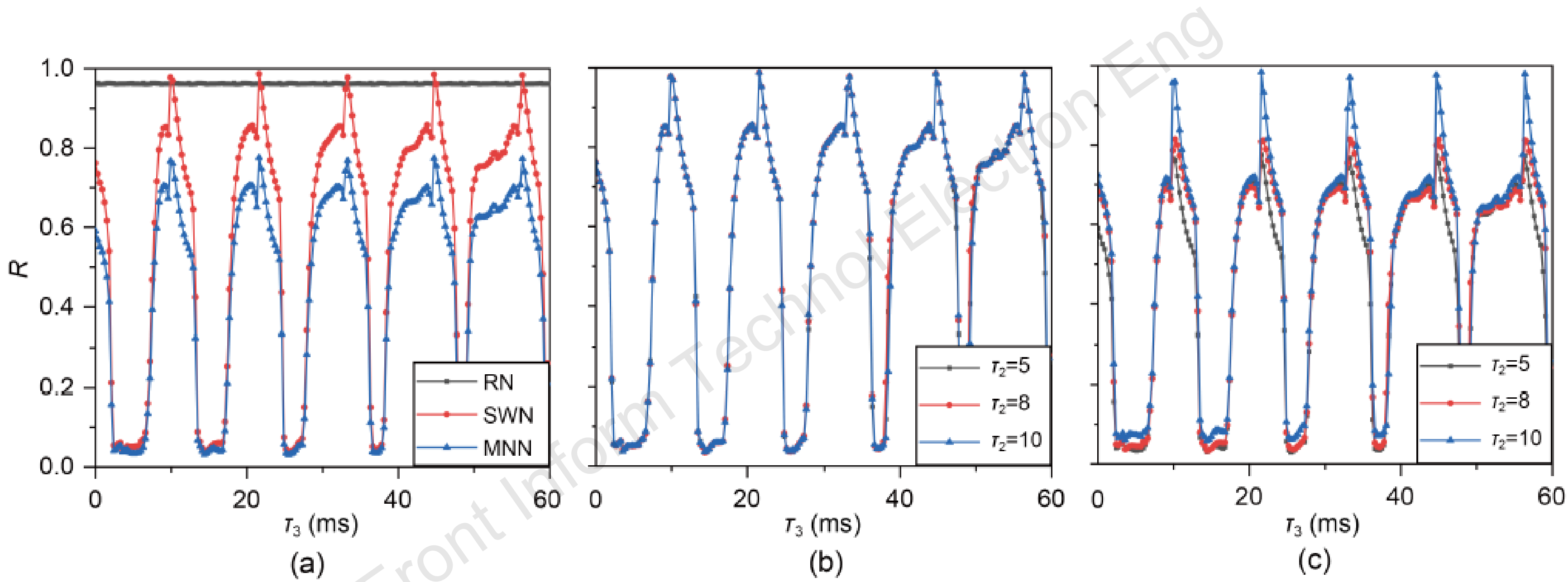

Fig. 6 Distribution of the synchronization factor in the network with increasing time delay τ_3: (a) variation of the synchronization factors of the three networks when τ_2=5; (b) variation of the synchronization factors of small-world network (SWN) when τ_2 is different; (c) variation of the synchronization factors of the modular neural network (MNN) when τ_2 is different (τ_1=10, g=0.1, and D=0.1)

Effect of time delay between two subnetworks on the synchronization of MNN

- τ_2 represents the time delay between neurons within a large-scale subnetwork.

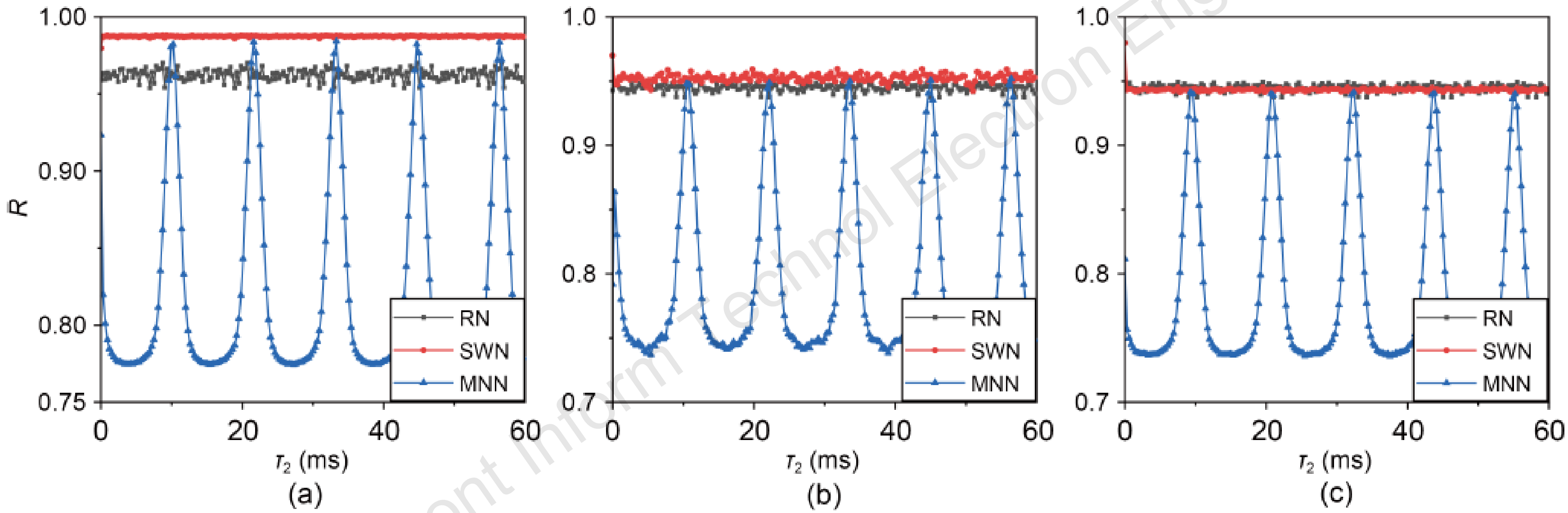

Fig. 7 Distribution of the synchronization factor in the network with increasing time delay τ_2: (a) τ_1=10, τ_3=10; (b) τ_1=21, τ_3=21; (c) τ_1=21, τ_3=10 (RN: random network; SWN: small-world network; MNN: modular neural network)
When the subnetworks are well synchronized internally, the synchronization factor of the modular neural network can be seen to increase and decrease periodically with the increase of the time delay τ_2

The mechanism of synchronization transition of MNN

- Δt represents the average phase difference between the two subnetworks.

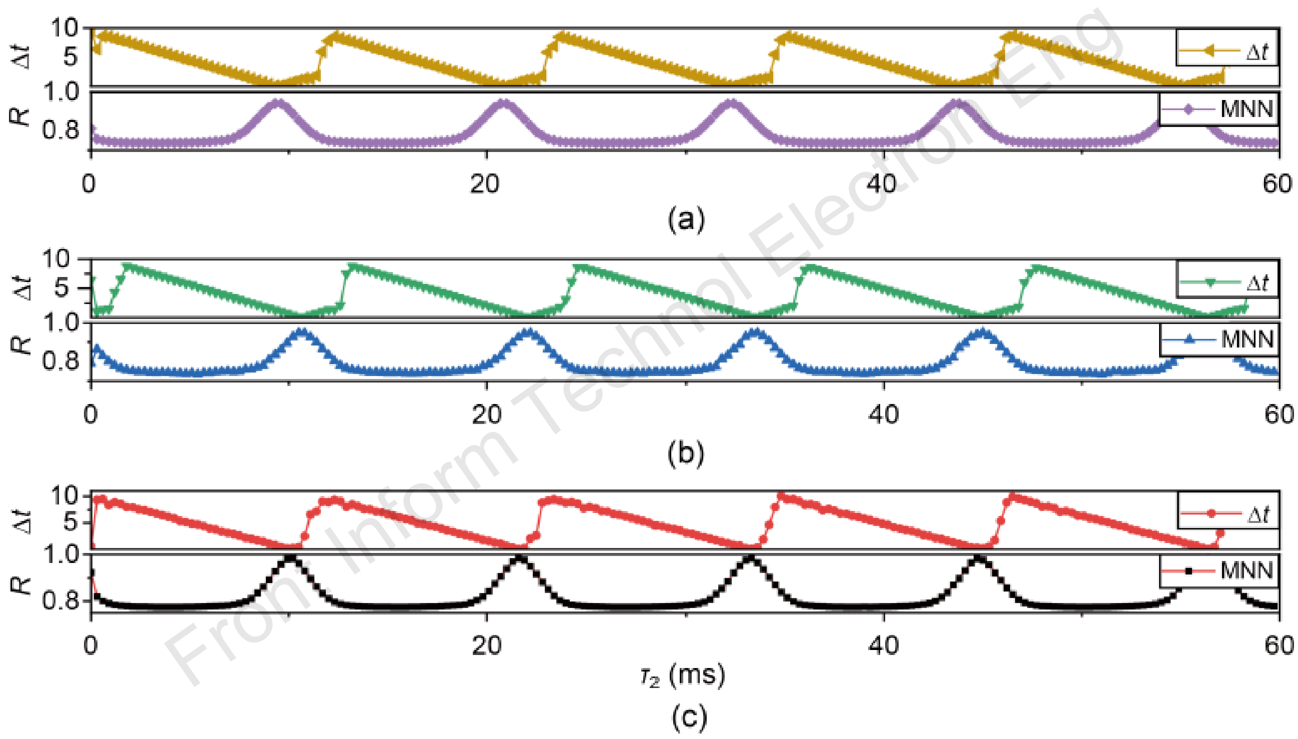

Fig. 8 Corresponding distribution of the phase difference and synchronization factor in modular neural networks (MNNs) with increasing time delay τ_2: (a) τ_1=21, τ_3=10; (b) τ_1=21, τ_3=21; (c) τ_1=10, τ_3=10

Conclusions

- When the time delays are all the same in MNN, the time delays are found to induce multiple synchronization transitions in the network. An increase in coupling strength also promotes the synchronization of the network when the time delay is an integer multiple of the firing period of a single neuron.
- When studying the effect of time delays at different locations in the MNN on the synchronization of networks, it is found that an increase in the time delay within both subnetworks induces multiple synchronization transitions of their own. The synchronization state of the small-scale network affectes the synchronization of the large-scale network. Whereas the time delays between two subnetworks can induce synchronization transitions in MNN, the mechanism behind this is the periodic variation of the phase difference between the subnetworks.

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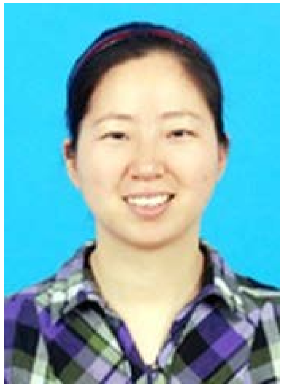

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