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Performance Evaluation of a Sensor Network Synchronization Scheme based on Noise Induced Phase Synchronization

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Abstract– We investigate a novel synchronization scheme, which does not require any signal exchange, by applying the noise-induced synchronization phenomenon. The noise-induced synchronization is a phenomenon that multiple nonlinear limit-cycle oscillators synchronize with each other by adding a common noise to each of them. As an application of this synchronization theory, we proposed a scheme that synchronizes wireless sensor network devises by using natural environmental signals obtained by the sensors on each. Our previous research showed that the neighboring nodes of the ZigBee sensor network synchronize by our scheme. It is because the time series of the sensed environmental data at each sensor, which are used as additive noise to the nonlinear oscillator of each, have higher cross-correlation. In our previous research, we considered environmental signals as acquired at constant intervals. In this paper, we investigate whether nonlinear limit-cycle oscillators can be synchronized even when there is variation in the acquisition time. Our results show that the synchronization can be achieved in such a more realistic and difficult situation.

1. Introduction

Wireless sensor networks (WSNs) are the networks of many sensor nodes, which acquire various kinds of context information. In order to distribute huge number of battery-powered wireless sensor nodes, it is important to optimize power efficiency. One of the approaches for such low-power consumption protocols is intermittent communications by synchronized sensor nodes [1]-[3]. Intermittent operation can extend the sleep time of sensor nodes, as a result, extend the network lifetime. In such an approach, the nodes of the sender and the receiver should be awake at the same time, so it is necessary the clock synchronization for wireless sensor nodes. One of simplest synchronization schemes are to exchange clock information between the sensor nodes using NTP based protocol [4], to receive GPS signals, and so on. However, those schemes have overheads in power consumption, such as wireless packet transmission, receiving of wireless signals, and so on.

As one of the most recent synchronization theory, the noise-induced synchronization phenomenon has been found by studies on various nonlinear dynamical systems, and its mathematical theory has been clarified [6-15]. By applying the same noises to uncoupled nonlinear oscillators having limit cycle orbit, the phase difference between the oscillators is reduced gradually, eventually synchronized.

We are investigating about new synchronization scheme applying the noise-induced phase synchronization phenomenon to synchronization of the wireless sensor nodes. We use natural noise in real environment as a common noise applied to each nonlinear limit-cycle oscillators running on each sensor, which synchronizes with each other. This proposed scheme may have an advantage over the existing synchronization schemes, since it does not require any packet exchanges for synchronization.

In order to investigate feasibility of the proposed system, we actually applied signals that was obtained by the sensor nodes to the nonlinear oscillators, and have confirmed that the synchronization can be achieved by the environmental signals [16]. At that time, we assumed that sensor nodes acquired environmental data constantly. However, in the case of real wireless sensor nodes such as the MICA Mote [17], the intervals of time are about 7 seconds in average but not constant. The interval of acquisition time may vary when a higher priority task is executed on the sensor node.

In this paper, we investigate feasibility of the proposed scheme in the case with such variation in the sensing intervals. We use real data obtained by the real wireless sensors [17], those sensing time interval is not constant, and analyze the changing of the phase differences among the limit-cycle oscillators on the wireless sensor nodes.

2. Noise-Induced Phase Synchronization Theory

We apply the noise-induced phase synchronization theory of the limit cycle nonlinear oscillators [6-15] to the time synchronization among the wireless sensor nodes. By inputting a common noise sequence to limit cycle nonlinear oscillators, they synchronize autonomously.

Since this theory does not require any interactions between the nonlinear oscillators for synchronization, it becomes possible to synchronize the clocks of the sensor nodes without any communications or signal exchanges between them by inputting very similar additive noises.

An ordinary differential equation of the dynamics of the oscillator is follows,

$$\dot{\mathbf{X}}(t) = \mathbf{F}(\mathbf{X}) \ . \quad (1)$$

The dynamics of the angular frequency of its phase is follows,

$$\dot{\theta}(t) = \omega \ . \quad (2)$$

Here, we consider two limit cycle oscillators which have common noise input to both. The dynamics of a limit cycle oscillators with the Gaussian white noise $\xi(t)$ can be expressed as follows,

$$\dot{\mathbf{X}}_1(t) = \mathbf{F}(\mathbf{X}_1) + \xi(t) \quad \dot{\theta}_1(t) = \omega + Z(\theta_1)\xi(t) \ , \quad (3)$$

$$\dot{\mathbf{X}}_2(t) = \mathbf{F}(\mathbf{X}_2) + \xi(t) \quad \dot{\theta}_2(t) = \omega + Z(\theta_2)\xi(t) \ , \quad (4)$$

where $Z(\theta) = grad_x \theta(\mathbf{X})\big|_{\mathbf{X}=\mathbf{X}_0(\theta)}$ is called the phase sensitivity function. When we assume that the difference of the phase is sufficiently small, the dynamics of the phase difference can be expressed as follows,

$$\phi = \theta_1 - \theta_2 \ . \quad (5)$$

Analyzing the linear growth rate (Lyapunov exponent average) of phase difference, Λ is calculated as follows,

$$\begin{aligned} \Lambda &= \left\langle \frac{d}{dt} \ln|\phi(t)| \right\rangle = \varepsilon^2 \left\langle Z''(\theta(t)) Z(\theta(t)) \right\rangle \\ &\cong \frac{\varepsilon^2}{2\pi} \int_0^{2\pi} Z''(\theta) Z(\theta) d\theta \\ &= -\frac{\varepsilon^2}{2\pi} \int_0^{2\pi} \{Z'(\theta)\}^2 d\theta \le 0 \ . \end{aligned} \quad (6)$$

Since the linear growth rate of the phase difference dynamics is smaller than 0 for the limit cycle, the phase difference always decreases. Thus, two limit cycle oscillators can be synchronized by adding a common noise for both.

3. Natural Environmental Signal Used as Common Noise of Noise-Induced Synchronization Phenomenon

In our proposed scheme, we apply natural signals to the oscillators as the common noise for noise-induced synchronization phenomenon. Each sensor runs the internal oscillator, and the clock will be adjusted according to the phase of the oscillator. Each sensor apply environmental signal that was obtained by itself to oscillator as common noise.

The wireless links used for the wireless sensor networks should be low power consumption and not possible to transmit the packets for the long distance. For example, MICAz [17] with ZigBee wireless system [18] that is used in this paper's experiment can transmit approximately 20m or less, for low packet error rate.

In such a short distance interval arrangement of the wireless sensors, the neighboring nodes may obtain the highly correlated natural signals. By applying such signals to uncoupled oscillators in the sensor nodes, the oscillators could be synchronized as shown in Ref. [16]. When the oscillators synchronize, the clock of the sensor, which is adjusted according to the phase of the oscillator running on it will synchronize with others. In our previous research [16], we confirmed that cross-correlation among the natural signals obtained in the neighboring wireless network sensors is actually higher in short-distance, and showed that the proposed scheme is feasible.

4. Synchronization of Nonlinear Oscillators Using Environmental Signals which has Variation in Time Interval

In our experiments, we apply our proposed scheme to the WSN, which collects natural signals, such as the temperature and the humidity, which can be obtained by MICAz with its sensor. We use the WSN on the outdoor corridor of first and second floors of Kudan building of Tokyo University of Science. The sensors were installed on walls and ceilings within 20 meters interval to the neighboring nodes. We have measured the natural environmental signals for three days, and normalize those signals for the synchronization experiments with keeping higher cross-correlation.

In our previous experiments [16], we assumed that the environmental signals are acquired at a constant interval by each sensor. However, the actual interval of data acquisition varies in the real wireless sensor nodes. One of the reasons is a fluctuation of the processing delay due to the higher priority tasks on sensor nodes. We investigate the feasibility of our proposed synchronization scheme using such data with inconstant time intervals.

In the following experiments, we use partial average of the sensing data with some time interval. Figure 1 shows the relationship between the time interval for the partial average and the cross-correlation of the averaged data. From Fig. 1, it is confirmed that the time interval for partial average should be more than 8.64 seconds of samples to keep cross-correlation higher, thus we use 8.64 seconds for the average. After creating the partially averaged time series of environmental data, we normalize them by subtracting simple moving average from them. In this paper, we use the samples of 4.32×10^2 minutes for the simple moving average. Figures 2 and 3 show examples of time series of the natural environmental data and its normalized data. We examine synchronization performance by applying such normalized signals to uncoupled nonlinear oscillators.

Figures 4 and 5 are the time series of phase differences between the two FitzHugh-Nagumo oscillators [16] which applied the normalized natural environmental signals. The normalized signals of humidity data acquired by node 1 and node 2 and temperature data acquired by node 1 and node 4 have 0.892 and 0.827 of cross-correlation value. The phase difference is calculated with difference of the times when oscillators pass through the phase zero. The phase difference converges to nearly 0 on both Figs. 4 and 5, and it is confirmed that the synchronization achieves. Figure 6 shows the time series of the values of v of FitzHugh-Nagumo oscillators [16] at the time they achieve synchronization. It can be seen that the waveforms of two different oscillators go overlapped to the other.

These results shows that the proposed method is feasible even for the sensing data obtained in inconstant intervals. Applying suitably normalized natural environmental signals to the nonlinear oscillators running in the sensor nodes, the oscillators in neighboring nodes will synchronize autonomously. Accordingly, the time synchronization of the sensor nodes can be realized without any other communications or interactions, by adjusting the internal clocks according to the phase of the nonlinear oscillators.

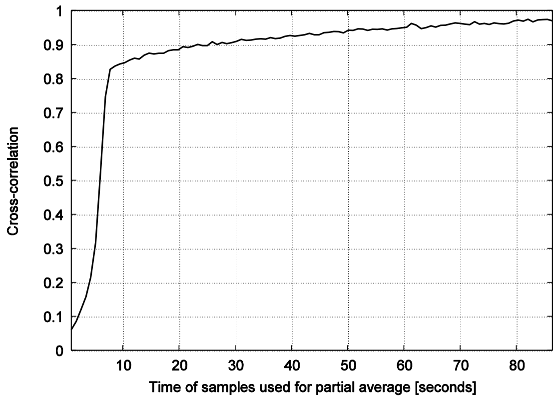

Figure 1. Relationship between the cross-correlation among the time series of partially averaged data of temperature on the different nodes and the number of data used for partial average.

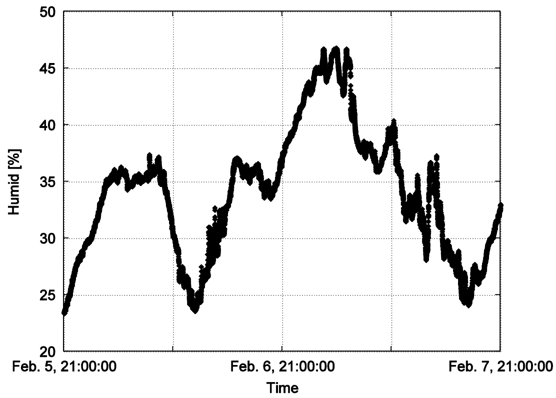

Figure 2. Time series of natural humidity data acquired by a wireless sensor node.

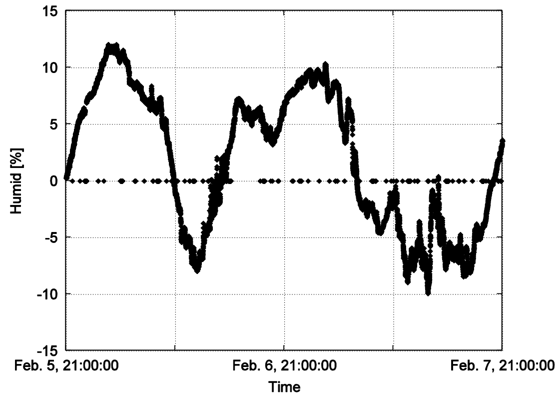

Figure 3. Time series of the normalized humidity data.

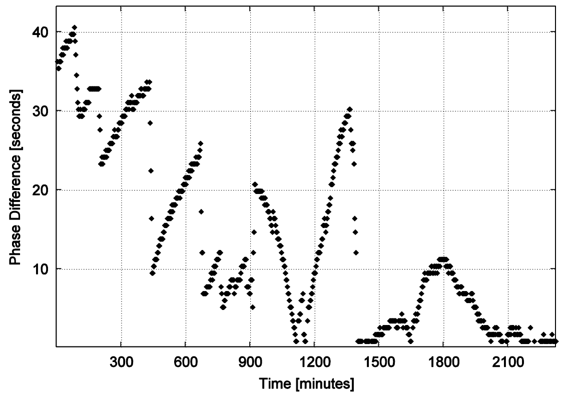

Figure 4. Phase difference between the FitzHugh-Nagumo oscillators in the Node 1 and the Node 2 with adding the humidity values sensed at each sensor.

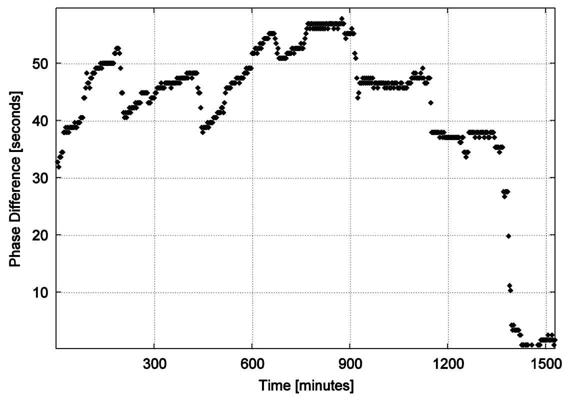

Figure 5. Phase difference between the FitzHugh-Nagumo oscillators in the Node 1 and the Node 4 with adding the temperature values sensed at each sensor.

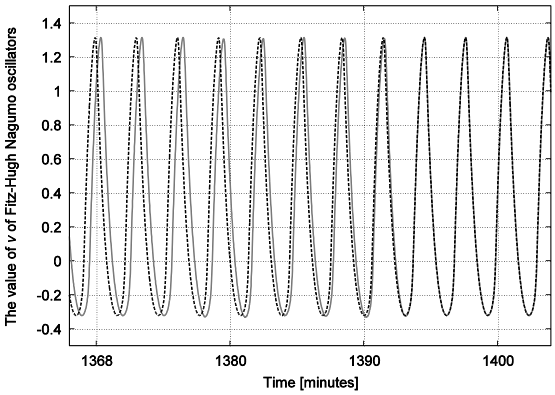

Figure 6. Noise Induced Phase Synchronization of the FitzHugh-Nagumo oscillators, to which humidity data of Node 1 and Node 2 are applied.

5. Conclusion

In this paper, we investigate feasibility of the proposed scheme in the case that the sensing intervals are fluctuating. We use the partial averages of the natural environmental data and normalize them by subtracting simple moving average from the partial average. We use 8.64 seconds and 4.32×10^2 minutes of partial average and moving average, respectively. By our experiments, we confirm that uncoupled nonlinear oscillators can synchronize by the normalized natural environmental data even for the case that the sensors collects natural data in inconstant interval

Our future works are to analyze the effective nonlinear oscillators and its parameters for improving the synchronization performance. We also would like to test its performance with real world experiments with larger number of sensor nodes in various locations, with actual implementation.

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