PAPER *Special Section on Progress in Information Network Science*

Natural Synchronization of Wireless Sensor Networks by Noise-Induced Phase Synchronization Phenomenon

Hiroyuki YASUDA[†a)], ***Nonmember and*** **Mikio HASEGAWA**[†b)], ***Member***

SUMMARY We propose a natural synchronization scheme for wireless uncoupled devices, without any signal exchange among them. Our proposed scheme only uses natural environmental fluctuations, such as the temperature or humidity of the air, the environmental sounds, and so on, for the synchronization of the uncoupled devices. This proposed synchronization is realized based on the noise-induced synchronization phenomenon, uncoupled nonlinear oscillators synchronize with each other only by adding identical common noises to each of them. Based on the theory of this phenomenon, the oscillators can also be synchronized by noise sequences, which are not perfectly identical signals. Since the environmental natural fluctuations collected at neighboring locations are similar to each other and cross-correlation becomes high, our proposed scheme enabling synchronization only by natural environmental fluctuations can be realized. As an application of this proposed synchronization, we introduce wireless sensor networks, for which synchronization is important for reducing power consumption by intermittent data transmission. We collect environmental fluctuations using the wireless sensor network devices. Our results show that the wireless sensor network devices can be synchronized only by the independently collected natural signals, such as temperature and humidity, at each wireless sensor device.

key words: *synchronization, nonlinear dynamics, oscillators, noise-induced synchronization, wireless sensor networks*

1. Introduction

Noise-induced phase synchronization [1]–[10] is a phenomenon that uncoupled nonlinear oscillators synchronize with each other only by adding common identical noise to the oscillators. This synchronization phenomenon does not require any signal exchanges or interactions between the oscillators, for synchronization. The theory of this phenomenon has been already clarified. By applying the same identical noise sequences to limit cycle orbit of the uncoupled nonlinear oscillators, the phase difference between the oscillators is gradually reduced, eventually converged to zero, and they can be synchronized.

Based on the noise-induced synchronization phenomenon, we propose a natural synchronization scheme for uncoupled wireless devices. We use environmental natural fluctuations, such as the temperature and the humidity of the air, environmental sounds and so on. Those environmental natural fluctuations obtained at the neighboring devices have high similarity. By adding such similar fluctuations to the devices, our proposed scheme realizes natural synchronization of those devices, without any interactions or exchanges of the signals.

In this paper, we investigate the feasibility of the proposed scheme using the real natural environmental fluctuations collected by wireless sensor network devices. We use the temperature and the humidity of the air, which can be collected easily by using off-the-shelf wireless sensor network devices.

For wireless sensor networks, synchronization among the sensor nodes is important to reduce power consumption. Since it is hard task to exchange batteries of large number of battery-powered wireless sensor nodes, it is important to develop low power consumption protocol. One of the approaches is intermittent data transmission with extending sleep time by synchronized sensor nodes [11]–[15]. Simplest synchronization schemes are to exchange clock information between the sensor nodes, to receive GPS signals, and so on. However, those schemes have overheads in power consumption.

First, we evaluate the cross-correlation among the natural fluctuations, collected at the neighboring locations. We also check the necessary cross-correlation for the noise-induced synchronization phenomenon, and confirm the feasibility of the proposed approach. Finally, we apply an online algorithm to normalize the natural fluctuation for inputting to the oscillators, and show the synchronization of the oscillators.

2. Noise-Induced Phase Synchronization Theory

This section shows the theory of the noise-induced synchronization phenomenon, which is the base of our proposed natural synchronization scheme.

At first, an ordinary differential equation of the dynamics of the oscillator is defined by the following equation,

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

The dynamics of its phase can be defined as follows using the angular frequency ω,

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

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

$$\dot{\mathbf{X}}_1(t) = \mathbf{F}(\mathbf{X}_1) + \epsilon\xi(t), \tag{3}$$

Manuscript received March 16, 2013.
Manuscript revised June 27, 2013.

[†]The authors are with the Department of Electrical Engineering, Tokyo University of Science, Tokyo, 125-8585 Japan.
a) E-mail: hirobacon@haselab.ee.kagu.tus.ac.jp
b) E-mail: hasegawa@ee.kagu.tus.ac.jp

DOI: 10.1587/transcom.E96.B.2749

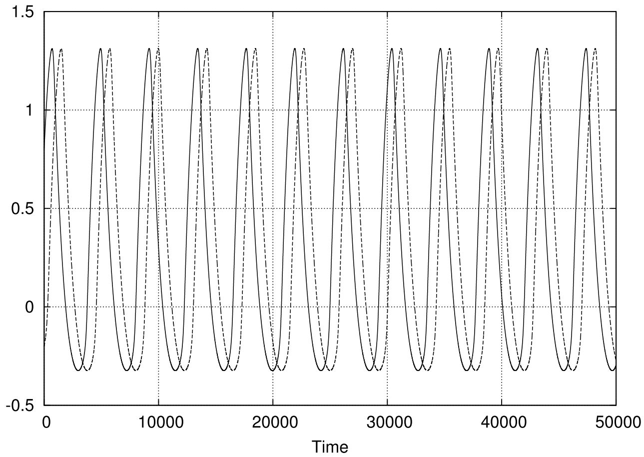


Fig. 1 Time series of the FitzHugh-Nagumo oscillators without any noises.

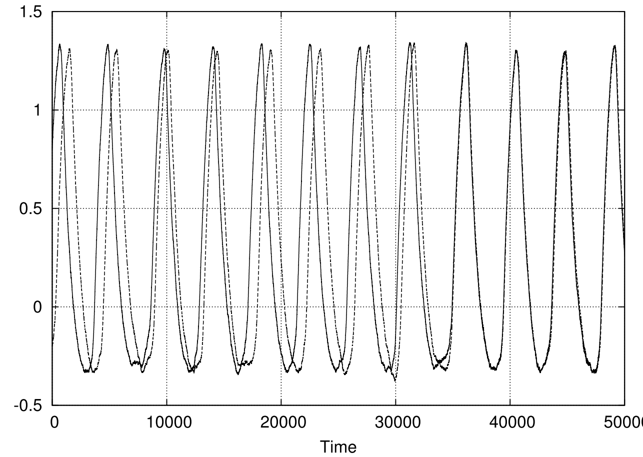


Fig. 2 Time series of the FitzHugh-Nagumo oscillators with common noise.

$$\dot{\mathbf{X}}_2(t) = \mathbf{F}(\mathbf{X}_2) + \epsilon\xi(t). \tag{4}$$

The phase dynamics of these oscillators with the common noise can be expressed as follows,

$$\dot{\theta_1}(t) = \omega + \epsilon Z(\theta_1)\xi(t) \tag{5}$$
$$\dot{\theta_2}(t) = \omega + \epsilon Z(\theta_2)\xi(t), \tag{6}$$

where $Z(\theta) = grad_{\mathbf{X}}\theta(\mathbf{X})|_{\mathbf{X}=\mathbf{X}_0(\theta)}$, which is called the phase sensitivity function. Here, we define the difference of the phases of these two oscillators as $\phi = \theta_1 - \theta_2$.

Analyzing the linear growth rate (the Lyapunov exponent average) of the phase difference, Λ, is calculated as follows [4],

$$\begin{aligned}\Lambda &= \left\langle \frac{d}{dt}\ln|\phi(t)| \right\rangle = \epsilon^2 \langle Z''(\theta(t))Z(\theta(t))\rangle \\ &\cong \frac{\epsilon^2}{2\pi}\int_0^{2\pi} Z''(\theta)Z(\theta)d\theta \\ &= -\frac{\epsilon^2}{2\pi}\int_0^{2\pi} Z'(\theta)^2 d\theta \leq 0.\end{aligned} \tag{7}$$

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.

There are various non-linear oscillators which have limit cycle attractor, such as the Stuart-Landau model or so on. In this paper, we use the FitzHugh-Nagumo (FN) oscillator, which is defined by the following equations,

$$\dot{v}(t) = v - v^3/3 - u + I \tag{8}$$
$$\dot{u}(t) = \varepsilon(v + a - bu) \tag{9}$$

where a, b and I are fixed parameters. In the first numerical experiment, we fix the parameters at ε= 0.08, a = 0.7, b = 0.8 and I = 0.4. Here, we show an example of the synchronization of this oscillator using the Gaussian white noise as the common noise, which is normalized to zero mean and 0.05 variance. Figures 1 and 2 show the time series of two FN oscillators, with and without the additive common Gaussian noise, respectively. From the Fig. 1, the difference of the phases of two FN oscillators does not change, and it depends only on the initial values of the oscillators. On the other hand, in Fig. 2, the two oscillators are gradually shifted and synchronized. It means that two oscillators can be synchronized by adding the common noise to the oscillators.

3. Natural Environmental Fluctuations Used as the Additive Sequences of Noise-Induced Synchronization

In our proposed scheme, we apply natural fluctuations to the nonlinear oscillators as the common noise of noise-induced synchronization phenomenon. As the natural environmental fluctuations, we use temperature or humidity of the air, environmental sounds and so on. Those fluctuations collected at neighboring devices become very similar to each other and the cross-correlation between the fluctuations obtained at the devices becomes high. Therefore, by using those fluctuations as the input noise to the nonlinear oscillators, they may synchronize with each other. As already described in the previous section, the nonlinear oscillators synchronize when the additive noise are identical. Our proposed scheme uses the natural fluctuations as additive noise, which are not identical but may have high cross-correlation. In this section, cross-correlation of the natural signals are evaluated and feasibility of the proposed scheme is investigated.

In our experiments, we measure the real natural environmental fluctuations using the wireless sensor network nodes, MICAz [16]. We evaluate the cross-correlation among the collected data by the sensor network nodes, which will be used as the additive fluctuations of our proposed synchronization scheme. By independently collecting natural fluctuations and adding them to the nonlinear oscillator at each wireless sensor network node, they can be synchronized by our proposed scheme and this synchronization does not require any packet exchange between the wireless sensor network nodes. Synchronization of the wireless

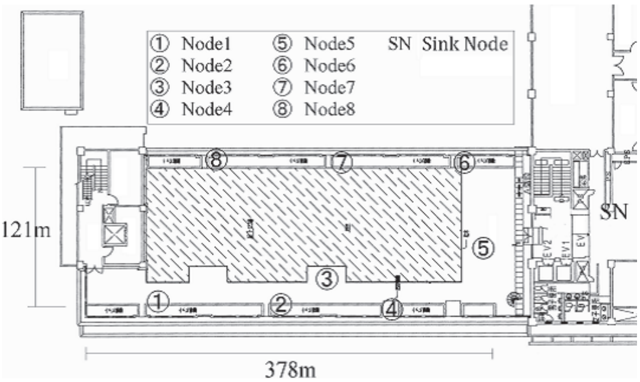


Fig. 3 Placement of the wireless sensor network nodes.

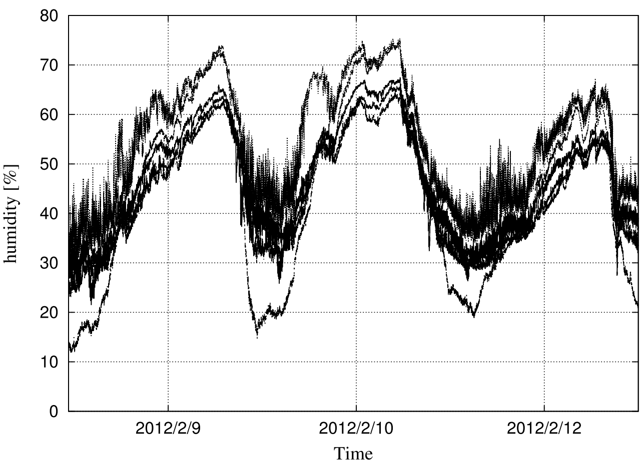


Fig. 4 Time series of natural environmental signals of humidity.

sensor network nodes is important for intermittent packet exchange for reducing power consumption. By using low power consumption oscillator circuit for each sensor, very low power synchronization can be realized by our proposed scheme. In this paper, we investigate feasibility of such a proposed scheme by investigating natural fluctuations independently collected at each sensor.

Figure 3 shows the arrangement of the wireless sensor network nodes. We distribute 8 sensor nodes on the rooftop garden of the Kudan building (7 floor building) of Tokyo University of Science. We measured the humidity and the temperature by using these wireless sensor nodes.

The time series of the measured time series by 8 sensor nodes are shown in Figs. 4 and 5 for the humidity and the temperature, respectively. Since the sensor nodes located in very small area and the distances between the nodes are around 10 to 30 m, the time series of these natural fluctuations have high similarity as shown in Figs. 4 and 5. The cross-correlation among these time series are shown in Tables 1 and 2 for the humidity and the temperature, respectively. From Tables 1 and 2, most of the cross-correlation values are around 0.8 or higher. Figures 6 and 7 show the relation between the distance and the cross-correlation. Even for the cases that the distances between the sensor nodes are

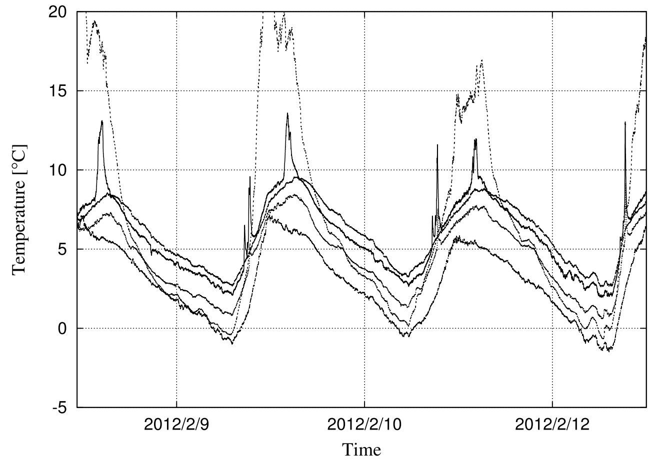


Fig. 5 Time series of natural environmental signals of temperature.

Table 1 Cross-correlation among the humidity time series measured at 8 sensors nodes.

Node	2	3	4	5	6	7	8
1	0.968	0.785	0.964	0.764	0.931	0.924	0.975
2	/	0.838	0.959	0.829	0.947	0.944	0.952
3	/	/	0.781	0.932	0.886	0.878	0.813
4	/	/	/	0.742	0.955	0.961	0.940
5	/	/	/	/	0.834	0.828	0.810
6	/	/	/	/	/	0.979	0.916
7	/	/	/	/	/	/	0.918

Table 2 Cross-correlation among the temperature time series measured at 8 sensor nodes.

Node	2	3	4	5	6	7	8
1	0.932	0.613	0.972	0.467	0.840	0.845	0.895
2	/	0.718	0.945	0.623	0.879	0.899	0.910
3	/	/	0.624	0.919	0.864	0.851	0.846
4	/	/	/	0.482	0.866	0.889	0.894
5	/	/	/	/	0.754	0.727	0.749
6	/	/	/	/	/	0.970	0.912
7	/	/	/	/	/	/	0.916

around 20 m or longer, the cross-correlation among the natural fluctuation still becomes 0.8 or higher, especially for the humidity data. From these measurement results, if the noise-induced phase synchronization could be achieved by the additive sequences whose cross-correlation are higher than 0.8, our proposed scheme enables to synchronize the sensor nodes only by the environmental data sensing, without any overhead communications between the wireless nodes.

4. Noise Induced Synchronization of Nonlinear Oscillators with Differences in Additive Noise

We investigate necessary cross-correlation for noise induced synchronization phenomenon. It has been already shown that two nonlinear oscillators can be synchronized by the common noise, as shown in Fig. 2 in many previous researches [4], [5]. However, necessary cross-correlation using different noise have not been clearly estimated. Therefore, in this section, we estimate the necessary cross-

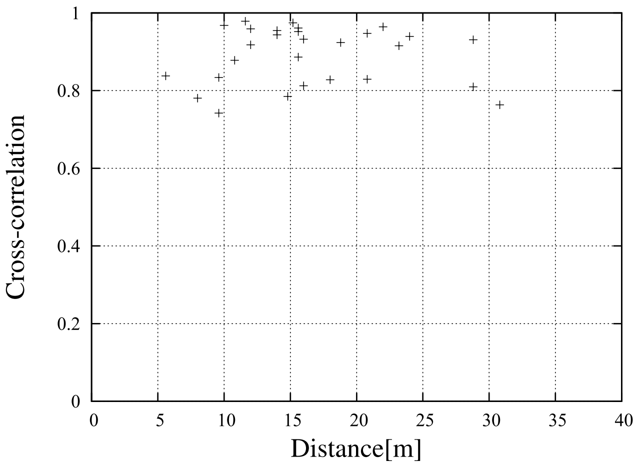


Fig. 6 Relationship between the distance and the cross-correlation among the humidity time series of the different nodes.

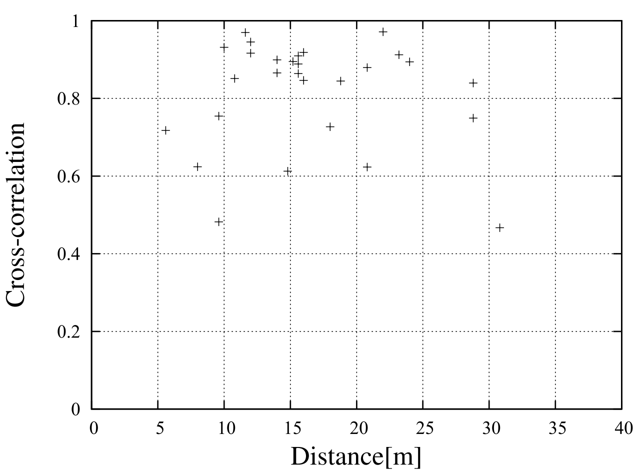


Fig. 7 Relationship between the distance and the cross-correlation among the temperature time series of the different nodes.

correlation by numerical computation experiments.

We evaluate the synchronization rate of the two FN nonlinear oscillators, with changing the cross-correlation between the additive Gaussian noise.

Figure 8 shows the relation between the cross-correlation among the additive Gaussian noise and the synchronization performance. The synchronization is defined as that phase difference of two oscillators remains within 5 degrees through 40 time periods. The synchronization performance is evaluated by the rate of the runs that two time series are synchronized in 1000 runs. The results in Fig. 8 clarify that high synchronization performance could be achieved when the cross-correlation values become around 0.8 or higher. Also in previous research, it is confirmed that synchronization can be achieved by not only white Gaussian noises but also other noises such as colored Gaussian noises and imperfectly common noises [19]. Moreover, [6]–[10] also show that other type of noises, such as Poisson noise, telegraphic current or so on, can achieve synchronization by noise-induced synchronization. These

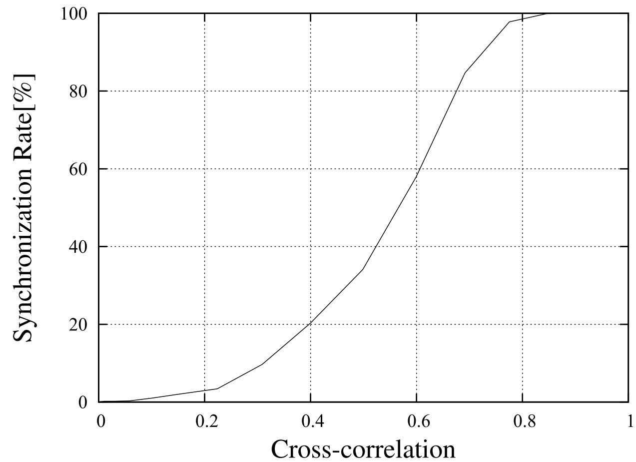


Fig. 8 Relationship between the cross-correlation and the synchronization performance.

results show, various type of signals are able to apply for input noise.

As already shown in previous section, the environmental fluctuations, such as the temperature and the humidity, collected at neighboring devices have high cross-correlation, 0.8 or higher. Therefore, the result in Fig. 8 shows that the natural signals with high cross-correlation enable noise-induced synchronization and that the proposed natural synchronization scheme is feasible.

5. Online Processing for Adding Collected Natural Fluctuations to Nonlinear Oscillators for Natural Synchronization

In order to realize the proposed natural synchronization, we need to normalize the collected data, because the most of the natural signals does not have zero mean and their amplitudes depend on the data type. In the original theory of noise-induced synchronization, it is assumed that noise is continuous and having zero means as the white Gaussian noise. In this section, we proposed an online processing scheme for wireless sensor networks to make the natural data suitable for being added to the nonlinear oscillators for noise induced synchronization. An important point is that this pre-processing should be an online algorithm, which can be applied at each step when the sensor data is collected.

In this paper, we focus on the synchronization of the wireless sensor network nodes. In the wireless sensor network node, actual intervals of data acquisition timing vary, since the processor of their processor is poor and scheduling is not perfectly constant. Furthermore, small undesirable noise is sometimes included in the obtained data.

When the temperature rises unexpectedly for some reason only at a particular node, the variation of the temperature would differ from the other nodes, and the cross-correlation may be reduced. Therefore, first of all, we take average value of some longer time interval. Second, as already described above, the obtained value of the natural fluctuations does not have zero mean. To make them to have zero mean

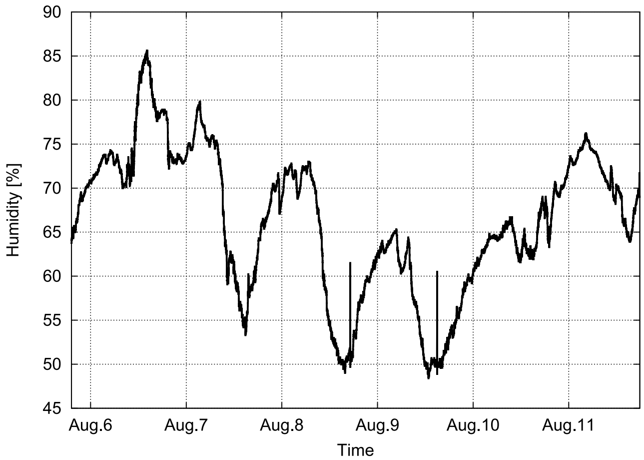


Fig. 9 Time series of raw humidity data.

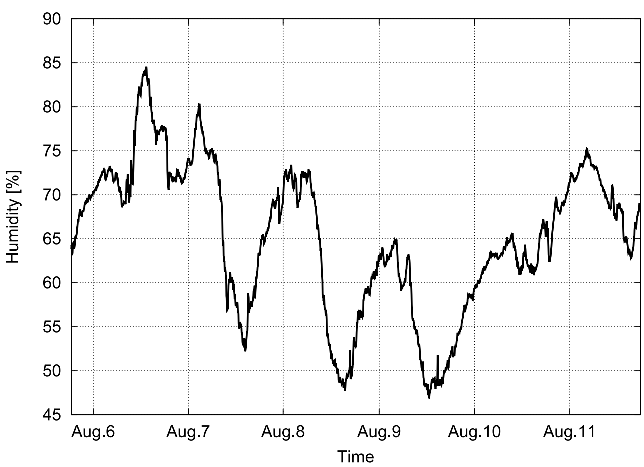


Fig. 10 Time averaged humidity data.

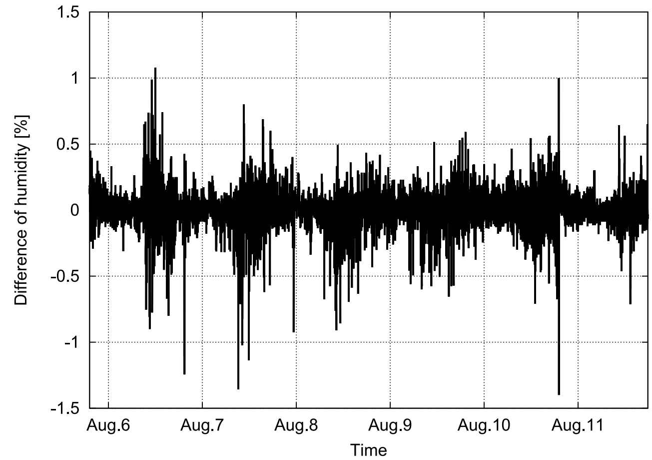


Fig. 11 The output of the difference filter.

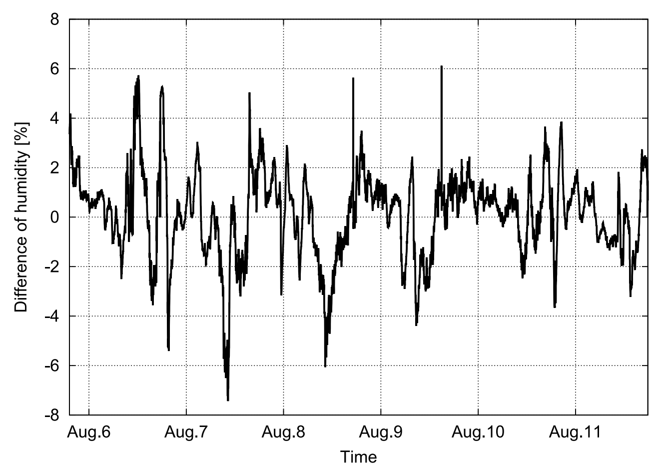


Fig. 12 The out put of the moving average filter.

for adding to the oscillators, we apply a difference filter, which takes differences of the values of the neighboring time steps, or a moving average filter, which subtracts moving average at time interval. The difference filter and the moving average filter are the methods that can be processed online.

Figure 9 shows an example of humidity data for 7 days collected by the wireless sensor network nodes. We apply time averaging with 180 seconds interval to the original data, and the time series shown in Fig. 10 is obtained. It can be seen that some sudden noises are suppressed with keeping variations of the original wave form. After creating the time-averaged environmental data, we make zero mean data by the difference filter or the moving average filter, as shown in Figs. 11 and 12. Thus, the input sequences for the nonlinear oscillators are generated for natural synchronization.

Figures 13 and 14 are the time series of phase differences between two FitzHugh-Nagumo oscillators, to which the normalized natural environmental signals are added. The difference filter and the moving average filter are applied to the humidity data acquired by node 1 and node 2. The cross-correlation between those generated time series are 0.892 and 0.827, respectively. The phase difference is time difference when oscillators pass through the phase zero. In this paper, we use the Runge-Kutta method which is a kind of approximate solutions in order to calculate the state of the oscillator.

From both Figs. 13 and 14, the phase difference converges to zero and it is confirmed that the synchronization is achieved. These results show that the proposed natural synchronization scheme is feasible for the sensing data obtained by the wireless sensor network node. However, the oscillators sometimes drop out the synchronized state by the input of noise. This problem should be solved to keep high performance of sustaining synchronization. In Ref. [20], we show that the noise input parameters, such as noise amplitude and interval, affect sustention of synchronization by our experiments.

Figure 15 shows the time series of the two oscillators with the natural signal inputs, which are normalized by the difference filter. The oscillators in the neighboring nodes synchronize autonomously, without any signal exchange between the nodes. Accordingly, the time synchronization of the sensor nodes can be realized without any other communications or interactions, by adjusting the internal clocks ac-

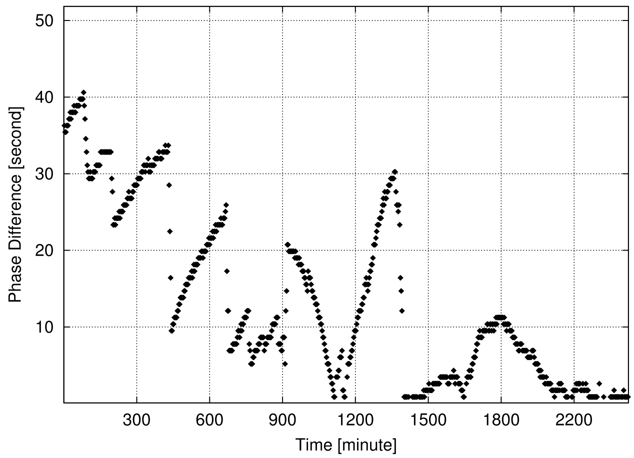


Fig. 13 Time series of the phase difference of oscillators with the output of difference filter.

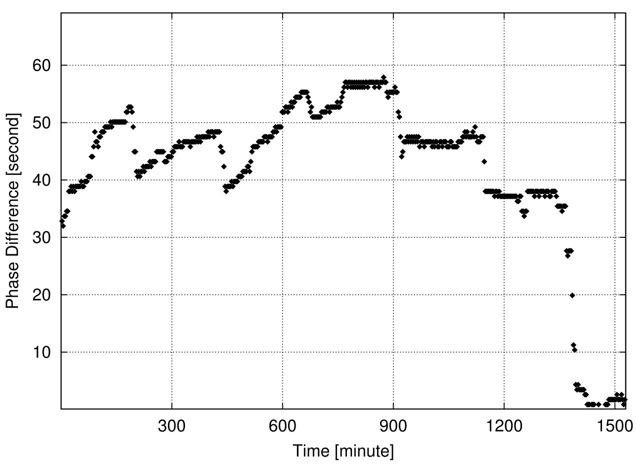


Fig. 14 Time series of the phase difference of oscillators with the output of moving average filter.

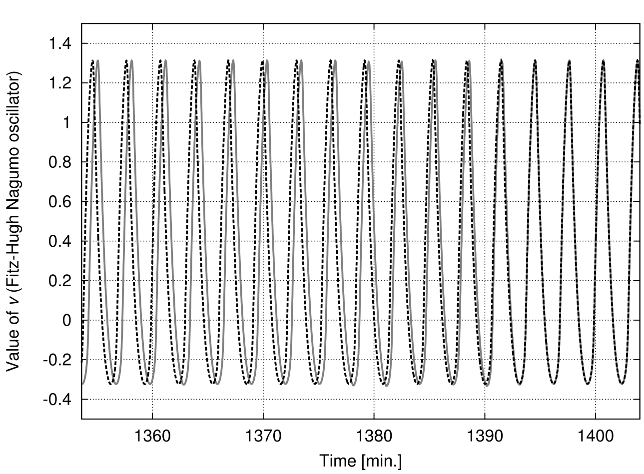


Fig. 15 Time series of the FitzHugh-Nagumo oscillators with adding natural environmental signal of humidity.

cording to the phase of the nonlinear oscillators.

6. Conclusions

In this paper, we propose a natural synchronization scheme of uncoupled devices, which does not require any signal exchange between them. We use environmental natural fluctuations for the synchronization of devices. The proposed scheme is based on the noise induced synchronization theory, the nonlinear oscillators synchronize with each other only by adding common identical noise to all of them. Since the environmental natural fluctuations obtained at neighboring devices are similar and having high cross-correlation, our scheme can synchronize the nonlinear oscillators running on each device only by adding the collected natural fluctuations independently. In order to enable the proposed scheme running sequentially, we apply an online algorithm to generate the data suitable for noise induced synchronization. By the numerical experiments using real obtained data by the wireless sensor network nodes, feasibility of the proposed natural synchronization scheme has been confirmed.

This paper showed the possibility of the synchronization without any interaction or signal exchange. We have already shown the feasibility of the proposed scheme using several kinds of natural environmental signals, such as temperature, humidity [17], and environmental sonic wave [18]. For improving time resolution of the proposed timing synchronization scheme, it is better to use higher frequency data. For higher synchronization performance, the higher cross-correlation signals are required.

Therefore, our most important future work is to investigate suitable natural signals for higher time resolution and higher synchronization performance. Also, we have to develop optimization scheme to determine parameter values of the proposed scheme, such as the time interval of adding the data to the oscillator, speed of the oscillator, strength of the additive signal to the oscillator, and so on. We also would like to find good applications, for which the proposed scheme is effective, because synchronization of the device clock becomes necessary for many systems, and the signal exchange is usually used in such systems. Our proposed scheme can eliminate such signal exchange and requires some sensor for obtaining natural signals. As one of the application, we would like to implement the low-power consumption wireless sensor network protocol having long sleep time, based on our proposed natural synchronization scheme. In the proposed scheme, it is necessary to calculate the state of the oscillators. Some power consumption is always necessary even though we use low power consumption oscillator circuit. Therefore, we would like also to make it our future work to evaluate the power consumption by using real devices, on which the proposed scheme is implemented.

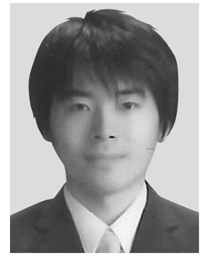
Acknowledgments

This research is partially supported by Aihara Innovative Mathematical Modeling Project, the Japan Society for the

Promotion of Science (JSPS) through the "Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)," initiated by the Council for Science and Technology Policy (CSTP).

References

[1] A.T. Winfree, The Geometry of Biological Time, Springer, 2001.
[2] Y. Kuramoto, Chemical Oscillations, Waves, and Turbulence, Dover, 2003.
[3] W. Horsthemke and R. Lefever, Noise-Induced Transitions, Springer, 1983.
[4] J. Teramae and D. Tanaka, "Robustness of the noise-induced phase synchronization in a general class of limit cycle oscillators," Phys. Rev. Lett., vol.93, 204103, 2004.
[5] H. Nakao, K. Arai, and Y. Kawamura, "Noise-induced synchronization and clustering in ensembles of uncoupled limit-cycle oscillators," Phys. Rev. Lett., vol.98, 184101, 2007.
[6] H. Nakao, K. Arai, and K. Nagai, "Synchrony of limit-cycle oscillators induced by random external impulses," Phys. Rev. E, vol.72, 026220, 2005.
[7] H. Nakao, K. Arai, K. Nagai, Y. Tsubo, and Y. Kuramoto, "Synchrony of neural oscillators induced by random telegraphic currents," Phys. Rev. E, vol.71, 036217, 2005.
[8] K. Arai and H. Nakao, "Phase coherence in an ensemble of uncoupled limit-cycle oscillators receiving common Poisson impulses," Phys. Rev. E, vol.77, 036218, 2008.
[9] K. Arai and H. Nakao, "Reproducibility of limit-cycle oscillators induced by random impulses," Proc. NOLTA, pp.295–298, 2006.
[10] S. Hata, K. Arai, R.F. Galan, and H. Nakao, "Optimal phase response curves for stochastic synchronization of limit-cycle oscillators by common Poisson noise," Phys. Rev. E, vol.84, 016229, 2011.
[11] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirc, "A survey on sensor networks," IEEE Commun. Mag., vol.40, pp.102–114, 2002.
[12] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," Proc. IEEE INFOCOM, vol.3, pp.1567–1576, 2002.
[13] J. Polastre, J. Hill, and D. Culler, "Versatile low power media access for wireless sensor networks," Proc. ACM SenSys, pp.95–107, 2004.
[14] S. Ganeriwal, R. Kumar, and M.B. Srivastava, "Timing-sync protocol for sensor networks," Proc. International Conference on Embedded Networked Sensor Systems, pp.138–149, 2003.
[15] M. Buettner, G.V. Yee, E. Anderson, and R. Han, "X-MAC: A short preamble MAC protocol for duty-cycled wireless sensor networks," Proc. ACM SenSys, pp.307–320, 2006.
[16] J. Hill and D. Culler, "Mica: A wireless platform for deeply embedded networks," IEEE Micro, vol.22, pp.12–24, 2002.
[17] M. Harashima, H. Yasuda, and M. Hasegawa, "Synchronization of wireless sensor networks using natural environmental signals based on noise-induced phase synchronization phenomenon," Proc. IEEE Vehicular Technology Conference Spring, 2012.
[18] Y. Honda, H. Yasuda, and M. Hasegawa, "Time synchronization scheme based on noise-induced synchronization using environmental sound," Proc. RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing, pp.125–128, 2013.
[19] W. Kurebayashi, K. Fujiwara, and T. Ikeguchi, "Colored noise induces synchronization of limit cycle oscillators," Europhysics Letters, vol.97, 50009, 2012.
[20] H. Yasuda and M. Hasegawa, "Experimental evaluation on feasibility of noise-induced synchronization by natural environmental signals," Proc. RISP International Workshop on Nonlinear Circuits, Communications and Signal Processing, pp.640–643, 2013.



Hiroyuki Yasuda received B.Eng. and M.Eng. degrees from Tokyo University of Science in 2011 and 2013. He is currently a doctor's student in Department of Electrical Engineering, Faculty of Engineering, Tokyo University of Science. His current research is noise-induced synchronization by natural environmental signals.

Mikio Hasegawa received B.Eng., M.Eng. and Dr.Eng. degrees from Tokyo University of Science in 1995, 1997 and 2000, respectively. From 1997 and 2000, he was a research fellow of the Japan Society for the Promotion of Science (JSPS). From 2000 to 2007, he was with Communications Research Laboratory (CRL), Ministry of Posts and Telecommunications, Japan, which was reorganized as National Institute of Information and Communications Technology (NICT) in 2004. Currently, he is an associate professor in Department of Electrical Engineering, Faculty of Engineering, Tokyo University of Science. His research interest includes mobile networks, cognitive radio, optimization algorithms, chaos theory and its applications.