Synchronization of Wireless Sensor Networks using Natural Environmental Signals Based on Noise-Induced Phase Synchronization Phenomenon

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Abstract—**We show that the wireless sensor networks can be synchronized by natural environmental signals, such as temperature, humidity and so on. The proposed synchronization scheme is based on the noise-induced phase synchronization theory; the phases of the periodical limit cycle orbits of nonlinear oscillators synchronize with each other by adding a common noise signal to the oscillators. Based on this theory, we synchronize the clocks of the wireless sensor nodes by tuning them according to the phase of their nonlinear oscillator to which natural environmental signals are added as noise. In this paper, first we analyze cross-correlation of the natural environmental signals measured by ZigBee wireless sensor nodes, which are arranged outdoor at about 20m intervals, and show that the cross-correlation among the signals sensed at different sensor nodes are around 0.8 or higher. According to this result, we analyze possibility of the noise-induced phase synchronization with changing cross-correlation between the additive noises, and clarify that the nonlinear oscillators can be synchronized in the cases that the cross-correlation becomes around 0.8 or higher. Finally, we investigate feasibility of the noise-induced phase synchronization by actual data of natural environmental signals sensed at each sensor node and show it is possible to synchronize wireless sensor nodes without any interactions or communications among them.**

Keywords-component; wireless sensor networks; nonlinear dynamics; noise-induced phase synchronization; limit cycle oscillators; power consumption

I. INTRODUCTION

The wireless sensor networks [1] are expected to be an important technical component in ubiquitous computing environment, to collect various kinds of context information from the real world. To collect information in wide area with high density by the wireless sensor networks, reduction of the power consumption becomes important, because it is not easy to exchange the battery of a huge number of wireless sensor nodes [2]—[5]. One approach for the power efficiency is to extend the sleep mode time in intermittent data transmission. In such an approach, the sender and the receiver nodes should wake up simultaneously, and synchronization of the clocks of the wireless sensor nodes becomes necessary, for realizing highly intermittent information exchange. The simple synchronization schemes are to exchange clock information between the sensor nodes using NTP based protocol [5], 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 recent synchronization theories, the noise-induced phase synchronization phenomenon has been investigated for various nonlinear dynamical systems, and its theory has been clarified [6][7]. By applying same noise to periodical limit cycle orbits of different nonlinear oscillators, the phase difference between those oscillators decreases gradually and finally they synchronizes, even though they have no interconnections with each other. In the wireless sensor networks, if the common noise can be applied to each node, they can be synchronized without any interactions, based on this theory.

In this paper, we apply the noise-induced phase synchronization phenomenon to synchronization of the wireless sensor nodes. This proposed scheme may have advantage over the existing synchronization schemes, since it does not require any packet exchanges for synchronization. In the proposed scheme, each wireless sensor node has own nonlinear oscillator in itself. The clock of each node is tuned according to the phase of the limit cycle orbit of the nonlinear oscillator. As the additive noise sequence to each nonlinear oscillator, we use the natural environmental data, such as temperature, humidity and so on, sensed at each sensor node. In our experiments, we use ZigBee based wireless sensor nodes whose transmission range is around 20m. In order to investigate feasibility of this system, first we evaluate cross-correlation of the natural environmental data collected at each sensor node. Then, we analyze possibility of synchronization by the noise-induced phase synchronization with changing the cross-correlation among the noise sequences input to each nonlinear oscillator. Finally, we apply actual data sensed at each sensor node to the nonlinear oscillators and investigate the synchronization performance of the proposed scheme on the wireless sensor networks for environmental monitoring.

II. NOISE-INDUCED PHASE SYNCHRONIZATION THEORY

In this paper, we introduce the noise-induced phase synchronization theory of the limit cycle nonlinear oscillators

[6][7], to the time synchronization among the wireless sensor nodes. By inputting a common noise sequence to the 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.

The dynamics of the phase of a limit cycle oscillator can be represented by the gradient as follows [8][9],

$$\dot{\theta}(t) = \mathrm{grad}_X \theta(\boldsymbol{X}) \cdot \dot{\boldsymbol{X}}(t) = \mathrm{grad}_X \theta(\boldsymbol{X}) \cdot \boldsymbol{F}(\boldsymbol{X}), \quad (1)$$

where $\dot{\boldsymbol{X}}(t) = \boldsymbol{F}(\boldsymbol{X})$ is an ordinary differential equation of the dynamics of the oscillator. The dynamics of the angular frequency of its phase, $\dot{\theta}(t) = \omega$, is defined as, $\mathrm{grad}_X \theta(\boldsymbol{X}) \cdot \boldsymbol{F}(\boldsymbol{X}) = \omega$. Here, the dynamics of the phase with perturbations $\boldsymbol{c}(\in \boldsymbol{R}^M)$ at $\boldsymbol{X}_0(\theta)$ is expressed by the following equation,

$$g(\theta; \boldsymbol{c}) = \theta(\boldsymbol{X}_0(\theta) + \boldsymbol{c}) - \theta. \quad (2)$$

Since the perturbation is small, the gradient of $\theta(\boldsymbol{X})$ is consistent with the dynamics of the phase. Therefore, the following equation is derived,

$$g(\theta; \boldsymbol{c}) \cong \mathrm{grad}_X \theta(\boldsymbol{X})\big|_{X=X_0(\theta)} \cdot \boldsymbol{c} = \boldsymbol{Z}(\theta) \cdot \boldsymbol{c}, \quad (3)$$

where $\boldsymbol{Z}(\theta) = \mathrm{grad}_X \theta(\boldsymbol{X})\big|_{X=X_0(\theta)}$ is called the phase sensitivity function.

The dynamics of the phase of a limit cycle oscillator with the Gaussian white noise $\xi(t)$ can be expressed as follows [10],

$$\dot{\theta}(t) = \omega + Z(\theta)\xi(t). \quad (4)$$

$\xi(t)$ satisfies $\langle \xi(t)\xi(s) \rangle = 2\delta(t-s)$, where $\langle \ \rangle$ indicates the average.

Here, we consider two limit cycle oscillators θ_1 and θ_2, which has common noise input for both. When we assume that the difference of the phase, $\phi = \theta_1 - \theta_2$, is sufficiently small, the dynamics of the phase difference ϕ can be expressed as follows using Eq. (4),

$$\begin{aligned} \dot{\phi}(t) &= Z(\theta_1(t))\xi(t) - Z(\theta_2(t))\xi(t) \\ &= (Z(\theta_1(t)) - Z(\theta_2(t)))\xi(t) \\ &= Z'(\theta(t))\phi(t)\xi(t), \end{aligned} \quad (6)$$

where $Z'(\theta(t)) = (Z(\theta_1(t)) - Z(\theta_2(t)))/(\theta_1(t) - \theta_2(t))$, because ϕ is sufficiently small. By analyzing the Lyapunov exponent of the phase, Λ, using the Novikov equation [11], it is calculated as follows,

$$\Lambda = \left\langle \frac{d}{dt} \ln|\phi(t)| \right\rangle = \langle Z''(\theta(t)) Z(\theta(t)) \rangle. \quad (6)$$

When the strength of the noise is sufficiently small, the phase of the limit cycle oscillator is uniformly distributed on the limit cycle [10]. Therefore, the average in Eq. (6) can be calculated as follows,

$$\begin{aligned} \Lambda &\cong \frac{1}{2\pi} \int_0^{2\pi} Z''(\theta) Z(\theta) d\theta \\ &= -\frac{1}{2\pi} \int_0^{2\pi} \{Z'(\theta)\}^2 d\theta \le 0. \end{aligned} \quad (7)$$

Since the Lyapunov exponent 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.

In this paper, we use FitzHugh-Nagumo oscillator. FN oscillator is defined as $\boldsymbol{X} = (u, v)$, $\dot{u}(t) = \varepsilon(v + a - bu)$ and $\dot{v}(t) = v - v^3/3 - u + I$, where ε, a, b and I are parameters. In the first numerical experiment, we fix the parameters at $\varepsilon = 0.08$, $c = 0.7$, $d = 0.8$ and $I = 0.4$. We add the Gaussian white noise to $\dot{u}(t)$ and $\dot{v}(t)$, so the equations of the oscillator can be expressed as $\dot{u} = \varepsilon(v + a - bu) + \lambda_1 \xi$ and $\dot{v} = v - \frac{v^3}{3} - u + I + \lambda_2 \xi$, where 1and2 are strength of the Gaussian white noise input. The additive Gaussian white noise ξ is normalized to zero mean and 0.05 variance, and added as the common noise sequence. The initial value was set $(u_1, v_1) = (0.8, 1.5)$, $(u_2, v_2) = (-0.2, -0.5)$. Figs. 1 and 2 show the time series of two nonlinear oscillators, with and without the additive common Gaussian noise. On 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. We apply this synchronization theory by the common noise to the sensor node synchronization.

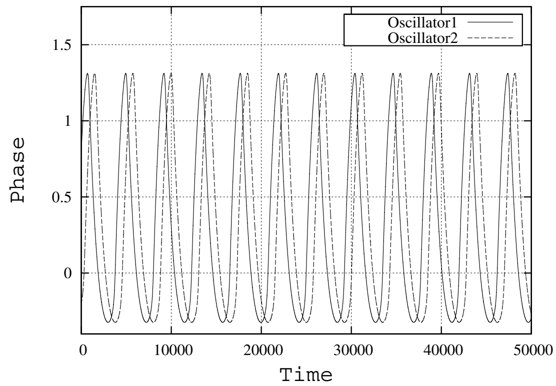

Figure 1. Time series of two nonlinear oscillators, FN, without any noise.

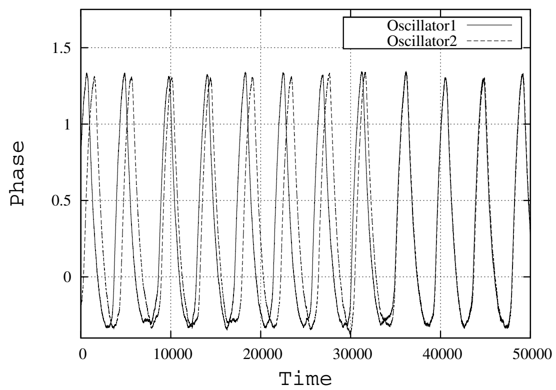

Figure 2. Time series of two nonlinear oscillators, FN, with common additive Gaussian white noise.

III. ACTUAL ENVIROMENTAL DATA AS THE COMMON NOISE FOR THE NOISE-INDUCED PHASE SYNCHRONIZATION

In our proposed scheme, we apply natural environmental signals, such as the temperature, humidity, atomosphere and so on, as the common noise to the noise-induced phase synchronization of the nonlinear oscillators. Each sensor node has the nonlinear oscillator running in itself, and the clock of each sensor is tuned based on the phase of the nonlinear oscillator in it. The measured value of the natural environmental signals at each instance is added to the nonlinear oscillator as the common noise.

We assume that 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. As one example, the MICAz, which uses ZigBee for the PHY/MAC, could transmit around 20m or shorter for low packet error rate, in our experiment. In such short distance, the neighboring sensor nodes may have almost the same environmental signal, and its temporal changing may be very similar. Thus, we use the normalized environmental signal directly as the common noise to the nonlinear oscillators for the noise-induced phase synchronization.

In order to confirm the similarity of the environmental signals of the neighboring nodes, we measure the real signals using the sensor nodes, MICAz, and evaluate the cross-correlation among the collected data, which will be used as the common signals. Fig. 3 shows the arrangement of the 8 sensor nodes. The location is the rooftop garden of Kudan building (7 floor building) of Tokyo University of Science. Measurement dates are 31st, May and 4th June, 2011. The weather was cloudy for both days. Humidity and temperature were measured. The sensor Node3 and Node5 shown in Fig. 3 are placed under the bench. The sensor Node1, Node2, Node4, Node6, Node7 and Node8 are placed on the edge of the flowerbed.

The time series of the measured data by 8 sensor nodes for the humidity and the temperature are shown in Figs. 4 and 5, respectively. The cross-correlation among these time series are shown in Tables 1 and 2. From Tables 1 and 2, many of the cross-correlation values are higher than 0.8. Figs. 6 and 7 show the relation between the distance and the cross-correlation between the nodes. Even for the cases that the intervals are 20m or longer, the cross-correlation becomes 0.8, especially on the humidity data. From these measurement results, if the noise-induced phase synchronization could be achieved by the noise with differences 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.

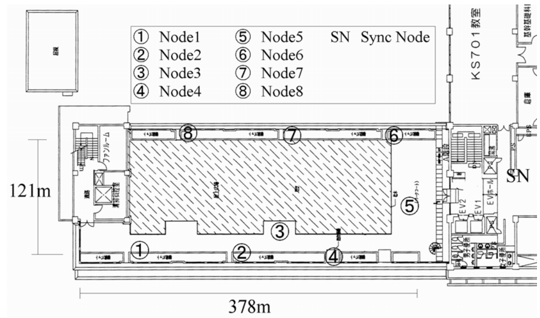

Figure 3. Placement of the nodes.

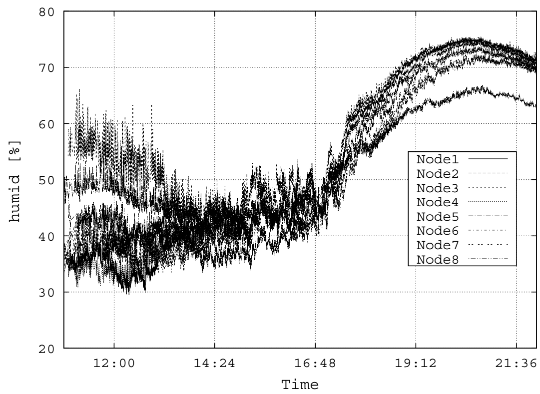

Figure 4. Time series of the humidity measured at 8 sensor nodes.

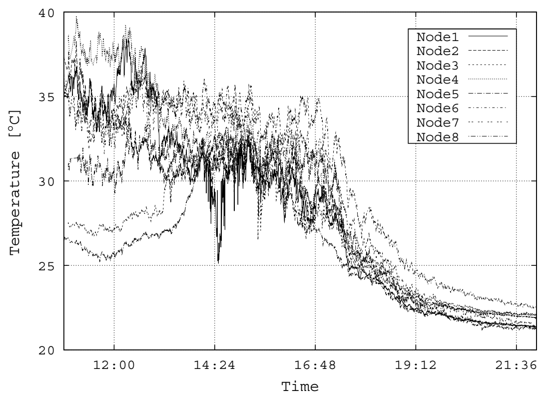

Figure 5. Time series of the temperature measured at 8 sensor nodes.

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**

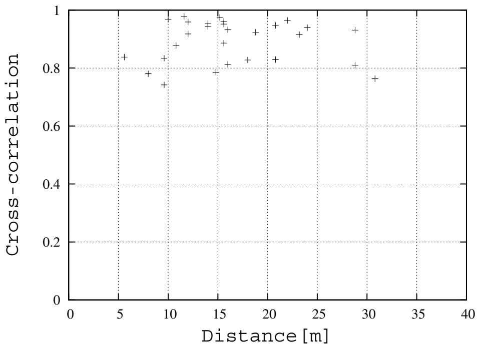

Figure 6. Relationship between the distance and the cross-correlation among the humidity time series of the different nodes.

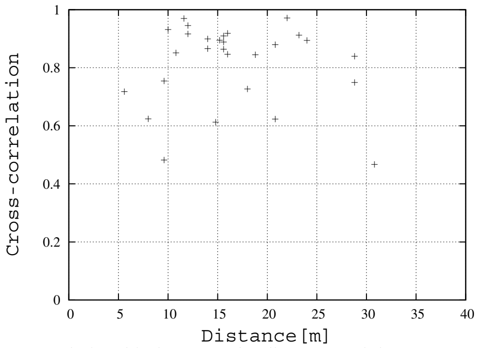

Figure 7. Relationship between the distance and the cross-correlation among the temperature time series of the different nodes.

IV. Analysis on Sychronizability of Nonlinear Oscillators with Differences in Additive Noise

We investigate the dependency of the synchronization performance on the cross-correlation. In this section, we use the slightly different Gaussian noise sequences with some cross-correlation , as the common noise sequence added to the nonlinear oscillators. We analyze the synchronizability of the two FN nonlinear oscillators, with changing the difference among the additive Gaussian noise. 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 [6]—[7],[10]—[15]. However, it is unknown whether it is possible to synchronize the oscillators when there are differences in the additive noise.

Fig. 8 shows the relation between the cross-correlation among the additive Gaussian noise and the synchronization performance. Synchronization performance is evaluated by the probability to synchronize the two time series. From the results in Fig. 8, it has been clarified that high synchronization performance could be achived when the cross-correlation values becomes 0.8 or higher.

As already shown in the previous section, the most of the cross-correlation values among the enviromental signal time series 0.8 or higher when the distance between the sensor nodes are upto 30m. Therefore, the results in Fig. 8 means that the enviromental signals, such as humidity and temperature, can synchronize the nonlinear oscillators in different sensor nodes, without any overhead communication between them.

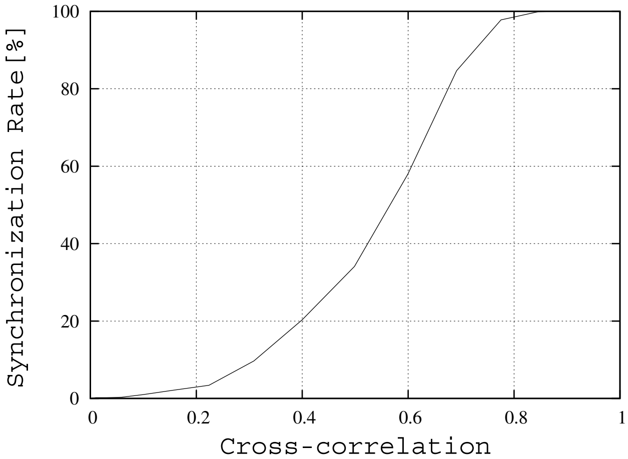

Figure 8. Relationship between the cross-correlation and the synchronization performance.

V. Application of Natural Environmental Signals to Noise-induced Phase Synchronization Wireless Sensor Node Synchronization

In this section, we apply the actual data of the natural environmental signals to the nonlinear oscillators in each sensor node, and investigate synchronization performance. In the following experiments, we use the data measured at the Node1 and the Node6. The cross-correlation between the time series measured at those nodes are 0.931 and 0.840 for the humidity and the temperature, respectively, as shown in Tables 1 and 2. Both time series are normalized to zero mean and 0.05 variance for adding to the nonlinear oscillators.

Figs. 9 and 10 show the difference of the phase between the FN oscillators in the Node1 and the Node6, for the humidity and the temperature, respectively. In both Figs. 9 and 10, the phase differences gradually converge to 0 that means two oscillators are synchronized. From these results, we confirm that our proposed system is feasible in our experimental environment. By tuning the clocks of each node based on the phase of the nonlinear oscillator in it, they can be synchronize without any interactions or communications between them.

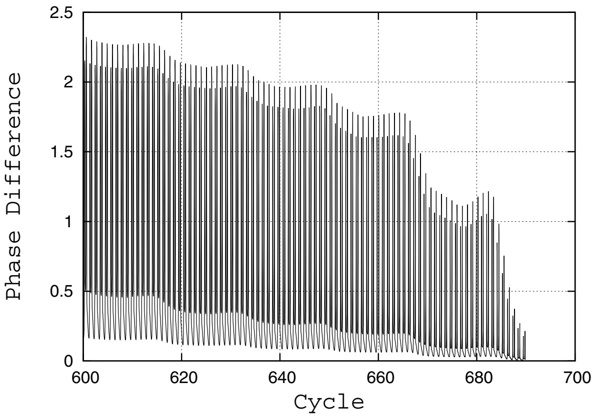

Figure 9. Phase difference between the FN oscillators in the Node1 and the Node6 with adding the temperature values sensed at each sensor.

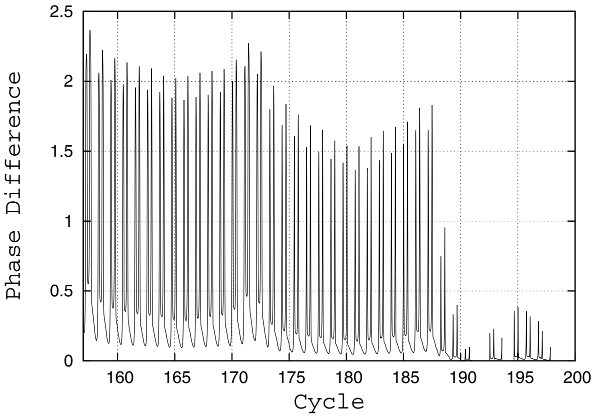

Figure 10. Phase difference between the FN oscillators in the Node1 and the Node6 with adding the humidity values sensed at each sensor.

VI. CONCLUSION

In this paper, we investigate the feasibility of our proposed scheme, which synchronizes wireless sensor nodes only by the natural environmental signals, such as the humidity and the temperature. We introduce the noise-induced phase synchronization theory for the synchronization without any interactions or communications between the sensor nodes. First, we measured the natural environmental signals using wireless sensor nodes, and showed that the cross-correlation between the humidity and the temperature time series of the neighboring sensor nodes become around 0.8 or higher for the ZigBee sensor network. Second, we investigated the synchronization performance with changing the cross-correlation among the additive noise, and clarified that the nonlinear oscillators can be synchronized when the cross-correlation is 0.8 or higher. Finally, we applied the raw environmental signals to the FN oscillators and showed that the phase difference converges to zero. This result means that wireless sensor nodes can be synchronized without any interactions or communications by tuning the clocks of each wireless sensor node according to the phase of the nonlinear oscillator in it with adding its own sensing data.

Our future works are to analyze the effective nonlinear oscillators and normalizing methods for improving the synchronization performance. We will also try real world experiments with larger number of sensor nodes in various locations.

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