CHAOS SYNCHRONIZATION-BASED DATA TRANSMISSION SCHEME IN MULTIPLE SINK WIRELESS SENSOR NETWORKS

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Abstract. This paper studies chaos synchronization-based data transmission scheme in multiple sink wireless sensor networks. In the proposed scheme, each wireless sensor node has a simple chaotic oscillator. The oscillators generate impulsive signals with chaotic interspike intervals, and are impulsively coupled by the signals via wireless communication. Each wireless sensor node transmits and receives sensor information only in the timing of the couplings. The proposed scheme can exhibit various synchronization and quasi-synchronization of chaos, and can effectively gather sensor information with low energy consumption. Also, the proposed scheme can flexibly adapt various wireless sensor networks not only with a single sink node but also with multiple sink nodes. We evaluate the proposed scheme using computer simulations. Through simulation experiments, we show effectiveness of the proposed scheme and discuss its development potential.

Keywords: Wireless sensor networks, Data gathering, Chaos, Synchronization, Pulse-coupled neural networks

1. Introduction. Wireless sensor networks (WSNs) have attracted a significant amount of interest from many researchers because they have great potential as a means of obtaining information of various environments remotely. WSNs have a wide range of applications, such as natural environmental monitoring in forest regions and environmental control in office buildings. In WSNs, hundreds or thousands of micro-sensor nodes with such resource limitation as battery capacity, memory, CPU and communication capacity are deployed without control in a region and used to monitor and gather sensor information of environments. Therefore, scalable and efficient network control and/or data gathering scheme for saving energy consumption of each sensor node is needed to prolong WSN lifetime. The sensor-to-sensor authenticated path-key establishment scheme [1] and the GA-based key-management scheme [2] can realize efficient secure communication in WSNs, considering WSN lifetime. The sink node allocation scheme [3,4] can find effective sink node allocation patterns to reduce total hop counts of all wireless sensor nodes, by using a particle swarm optimization which is a kind of meta-heuristics algorithms. As a result, this scheme can prolong WSN lifetime. Ant-based algorithms [5-8] have attracted attention as routing algorithms for energy consumption savings because they are more scalable, efficient and robust than other conventional routing algorithms [9-12], [13,14], which are composed of cluster-based mechanisms, are energy-efficient data gathering scheme. However, these routing algorithms are not applicable when network topology changes.

On the other hand, there has been a synchronization-based data gathering scheme (SDGS) that synchronizes wireless sensor nodes in the timing of gathering sensor information and that transmits sensor information of each wireless sensor node to sink nodes.
Using the SDGS, power supply of transceivers can be turned off when wireless sensor nodes do not transmit or relay sensor information, and the number of transmitting and receiving sensor information can be reduced. Hence, energy consumption of each wireless sensor node can be saved. As a hardware module along this line, the passive wake up scheme has been proposed [15]. This scheme wakes up a wireless sensor node that indeed needs to wake up. [16] has been presented interesting SDGS based on a pulse-coupled oscillator model, named the pulse-coupled neural network (PCNN) [17,18]. In the SDGS, each wireless sensor node has a timer characterized by an integrate-and-fire neuron [19], and is synchronized to each other rapidly through the pulse-couplings. Also, in the SDGS, it is assumed that each wireless sensor node communicates based on flooding. That is, each wireless sensor node does not have specific routing tables, and does not use any complex routing algorithms. It can contribute to energy consumption savings in resources such as memory and CPU of each wireless sensor node. However, simple PCNNs can exhibit periodic synchronization only. Therefore, in the SDGS presented in [16], the same sensor information tends to be relayed by many wireless sensor nodes. As discussed in [13], energy consumption of transceivers in transmitting sensor information is a dominant factor in WSNs. Such a redundant relay should be improved, and the total number of transmissions in WSNs should be reduced.

In our previous works, we have proposed a chaos-based data gathering scheme (CDGS) [20] using chaotic pulse-coupled neural networks (CPCNN) [21,22]. In the CDGS, each wireless sensor node has a simple chaotic oscillator. The oscillators generate spike-trains with chaotic interspike intervals, and are impulsively coupled by the spike-trains via wireless communication. Each wireless sensor node transmits and receives sensor information only in the timing of the couplings. The CDGS can exhibit various synchronization and quasi-synchronization of chaos, and each wireless sensor node can be synchronized partially and intermittently to each other. Such phenomena can flexibly reduce that the same sensor information is relayed by many wireless sensor nodes. However, the conventional SDGS and CDGS consider WSNs only with a single sink node. In the view points of practical applications, SDGS and CDGS not only in single sink WSNs but also in multiple sink WSNs should be considered in more detail. In both SDGS and CDGS, it is assumed that sink nodes broadcast stimulus spike signals for synchronization and wireless sensor nodes forward the signals. For effective data gathering, sink nodes should be allocated in an observation area where they are distant from each other [3,4]. If the sink nodes are not coupled to each other via direct wireless communication, it is hard to synchronize all the wireless sensor nodes.

This paper studies transmission efficiency of the CDGS in single sink and multiple sink WSNs. In Section 2, a model of the CDGS is explained, and typical phenomena from a simple master-slave network are presented. Then, a basic mechanism of partial and intermittent synchronization in the CDGS is discussed. In Section 3, simulation results for two types of WSNs, a single sink WSN and a multiple sink WSN, are presented. In the CDGS, wireless sensor nodes can exchange sensor information only when they are synchronized partially and intermittently to each other. The CDGS can effectively gather sensor information, reducing total number of relays of sensor information with keeping high delivery ratio. Also, the CDGS can flexibly adapt various WSNs not only with a single sink node but also with multiple sink nodes. Through simulation experiments, we show effectiveness of the CDGS and discuss its development potential.

2. Chaos-based Data Gathering Scheme. First, a chaos-based data gathering scheme (CDGS) using a chaotic pulse-coupled neural network (CPCNN) proposed in [20] is explained. We consider a wireless sensor network (WSN) consisting of $M$ wireless sensor
nodes. Each wireless sensor node $S_i \ (i = 1, \ldots, M)$ has a timer which controls timing to transmit and receive sensor information. The timer in $S_i$ is characterized by an oscillator having two internal state variables $x_i$ and $y_i$, a non-negative integer distance level $l_i$ and an offset time $\delta_i$. Basic dynamics of the timer in $S_i$ is described by the following equation.

$$ \frac{d}{dt} \begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix} = \begin{bmatrix} \Delta_i & \omega_i \\ -\omega_i & \Delta_i \end{bmatrix} \begin{bmatrix} x_i(t) \\ y_i(t) \end{bmatrix}, \text{ for } x_i(t) < 1 \text{ and } x'_{N(i)}(t) < 1 $$

(1)

$$ \begin{bmatrix} x_i(t^+) \\ y_i(t^+) \end{bmatrix} = \begin{bmatrix} q_i \\ y_i(t) - p_i(x_i(t) - q_i) \end{bmatrix}, \text{ if } x_i(t) = 1 $$

(2)

$$ \begin{bmatrix} x_i(t^+) \\ y_i(t^+) \end{bmatrix} = \begin{bmatrix} 0 \\ y_i(t) - p_i(x_i(t) - a_i) \end{bmatrix}, \text{ if } x'_{N(i)}(t) = 1 $$

(3)

where $\Delta_i$, $\omega_i$, $p_i$, $q_i$ and $a_i$ denote a damping, a self-running angular frequency, a slope in firing, a base state for self-firing and a base state for compulsory-firing, respectively. Hereafter, for simplicity all the wireless sensor nodes are assumed to have the same parameters. $R_C$ denotes radio range of wireless sensor nodes and sink nodes. $x'_{N(i)}$ is a virtual internal state variable of the neighbor wireless sensor node $S_{N(i)}$ described by

$$ x'_{N(i)}(t) = x_{N(i)}(t + \delta_{N(i)}) $$

(4)

That is, $x'_{N(i)}$ represents the virtual internal state variable considered the offset time $\delta_{N(i)}$. If the internal state variable $x_i$ reaches the threshold 1, $S_i$ exhibits self-firing, and the internal state $(x_i, y_i)$ is reset to the base state based on Equation (2). If the virtual internal state variable $x'_{N(i)}$ reaches the threshold 1, $S_i$ exhibits compulsory-firing and the internal state $(x_i, y_i)$ is reset to the base state based on Equation (3). After $S_i$ exhibits compulsory-firing, $S_i$ does not exhibit the next compulsory-firing during an offset time $\delta_i$. That is, $S_i$ has a refractory period $\delta_i$. It should be noted that the unit oscillator presented in [16] has one internal state variable, and can exhibit periodic phenomena only. The unit oscillator of the proposed CDGS has two internal state variables $x_i$ and $y_i$, and can exhibit various chaotic and bifurcating phenomena [21,22]. Also, it can generate chaotic spike-trains such that series of interspike intervals is chaotic.

Figure 1 shows a typical chaotic attractor from a unit oscillator without couplings. As $\Delta_i > 0$, the trajectory rotates divergently around the origin. If the trajectory reaches the threshold, it is reset to the base state based on Equation (2). Repeating in this manner, this oscillator exhibits a chaotic attractor. Figure 2 shows typical phenomena from a simple master-slave network consisting of two oscillators, where $M = 2$, $N(1) = \emptyset$ and $N(2) = \{1\}$. As shown in the figure, the first (master) oscillator exhibits chaotic attractors for both $q_i = -0.2$ and $q_i = 0.6$. The second (slave) oscillator is synchronized to the first
oscillator for \( q_i = -0.2 \). That is, the network exhibits master-slave synchronization of chaos. On the other hand, the second oscillator is not synchronized but quasi-synchronized to the first oscillator for \( q_i = 0.6 \). These phenomena can be explained by error expansion ratio between the master and slave trajectories [21]. We focus on the case \( a_2 = 1 \). Let \( t_n \) be the \( n \)-th compulsory-firing time of the slave oscillator, let the slave trajectory starts from \((q_i, y_2(t_n^+))\), and let the virtual master trajectory starts from \((q_i, y_1'(t_n^+))\). Let us consider that the \((n + 1)\)-th compulsory-firing of the slave oscillator occurs at \( t = t_{n+1} \) and that each trajectory is reset to each base state. Then, the following average error expansion ratio is defined.

\[
\bar{\sigma} = \frac{1}{N} \sum_{n=1}^{N} \ln \alpha_n, \quad \alpha_n \equiv \frac{|y_1'(t_{n+1}^+) - y_2(t_{n+1}^+)|}{|y_1'(t_n^+) - y_2(t_n^+)|} 
\] (5)

If the average error expansion ratio is negative for \( N \to \infty \), the slave oscillator is synchronized to the master oscillator as shown in Figure 2(a). Otherwise, the slave oscillator is not synchronized to the master oscillator. However, depending on sequence \( \{\alpha_n\} \), the slave oscillator can be intermittently synchronized to the master oscillator as shown in Figure 2(b). Such quasi-synchronization is important for effective data gathering by the CDGS. Basically, the sequence \( \{\alpha_n\} \) is determined by the parameters and initial states of the master and slave oscillators.

Distance levels of each wireless sensor node are adjusted in the following manner (see Figure 3). At first, each wireless sensor node has a sufficient large distance level. A sink node broadcasts level “0” as a beacon signal. Then, each wireless sensor node forwards the beacon signal by using flooding, and adjusts each own distance level as corresponding to hop count to its nearest sink node. The beacon signal is transmitted when each wireless sensor node exhibits compulsory-firing. That is, a wireless sensor node \( S_i \) adjusts own

\[\text{Figure 2. Typical phenomena from a master-slave CPCNN, left: master attractors, center: slave attractors, right: phase relationships, } \Delta_1 = 0.25, \omega_i = 5, p_i = 1, a_i = 1, \delta_i = 0, \text{ (a) synchronization of chaos: } q_i = -0.2, \text{ (b) quasi-synchronization of chaos: } q_i = 0.6\]
distance level $l_i$ as follows:

$$l_i = l_{N(i)} + 1, \text{ if } x'_{N(i)} = 1$$

$$N(i) = \{j \mid l_j < l_i, |S_j - S_i| < R_C\}$$

As a result, each wireless sensor node has a distance level as corresponding to hop count to its nearest sink node.

Sensor information is transmitted and received in the timing of *self-firing* (see Figure 4). When a transmitting wireless sensor exhibits *self-firing*, it broadcasts sensor information to the neighbor wireless sensor nodes. If all the following conditions are satisfied, it is assumed that sensor information can be relayed.

- A transmitting wireless sensor node has a larger distance level than a receiving wireless sensor node.
- The transmitting wireless sensor node exhibits *self-firing* earlier than the receiving wireless sensor node.
- Time interval for the above *self-firings* is within a constant period $t_r$.

Due to couplings considered offset time, wireless sensor nodes having large distance levels can transmit sensor information earlier than those having small distance levels as synchronization is achieved. As the offset time is set to sufficiently large value considered confrontations in MAC layer, the sensor information can be relayed sequentially from wireless sensor nodes far from sink nodes. If CDGS exhibits quasi-synchronization, it is not guaranteed that all sensor information must be transmitted to sink nodes. However, energy consumption of transceivers in transmitting sensor information is a dominant factor in WSNs [13]. The quasi-synchronization can reduce redundant relays such that the same sensor information is relayed to sink nodes, and can reduce the total number of transmissions in WSNs. It can contribute to prolonging WSN lifetime. Also, for effective data gathering, sink nodes should be allocated in an observation area where they are distant from each other [3,4]. If all the sink nodes are not coupled to each other via direct wireless communication, it is hard to synchronize all the wireless sensor nodes. The quasi-synchronization can flexibly adapt various WSNs not only with a single sink node but
also with multiple sink nodes. These advantages can be confirmed by the simulation experiments in the next section.

3. Numerical Simulations. In order to confirm effectiveness of the CDGS, we perform numerical simulations. Figure 5(a) shows a WSN model for the simulations. In the figure, 200 wireless sensor nodes are set at random on 8 concentric circles whose centers are (5, 0) or (−5, 0), and 2 sink nodes are set on each center. In the simulations for a single sink WSN, let only the left center node at (−5, 0) be a sink node and let the right center node at (5, 0) be a wireless sensor node. The radio range of each wireless sensor node and each sink node is set to 5. The radii of the concentric circles are set to 3, 6, 9 and 12, respectively. 10\text{m} wireless sensor nodes are set on the \text{m}-th concentric circle from each center. Figure 5(b) shows all the paths along which direct wireless communication between wireless sensor nodes is possible. Initial values of internal states in each wireless sensor node are set to random values. In the CDGS, the parameters are fixed as follows.

\[
\Delta_i = 0.25, \quad \omega_i = 5, \quad p_i = 1, \quad \delta_i = 0.2, \quad a_i = 1. \quad (7)
\]

Selecting \(q_i\) as a control parameter, typical simulation results are shown. Figure 6 shows self-firing time of each wireless sensor node. Horizontal axis denotes time, and vertical axis denotes the indexes of each wireless sensor node. Lower part of these figures shows the indexes of wireless sensor nodes and a sink node on the left concentric circles, and upper part shows them on the right concentric circles. Figure 7 shows internal states on phase plane at a time point in the steady state. In these figures, internal states of sink nodes are explicitly shown.

First, the results in the case of the single sink WSN are discussed. Figures 6(a) and 7(a) show the results in the case of the single sink WSN and \(q_i = -0.2\). All internal states are synchronized to each other with time difference depending on their own distance levels. Because, due to couplings considered offset time, wireless sensor nodes having large distance levels can transmit sensor information earlier than those having small distance levels as synchronization is achieved. We can also see that each sequence of the firing time is chaotic. Figures 6(b) and 7(b) show the results in the case of the single sink WSN and \(q_i = 0.6\). Internal states are not synchronized to each other. However, some regularities of self-firings can be found. The master-slave network exhibits synchronization of chaos in \(q_i = -0.2\) as shown in Figure 2(a), and exhibits quasi-synchronization of chaos in \(q_i = 0.6\) as shown in Figure 2(b). That is, the corresponding phenomena can be found.
Next, the results in the case of the multiple sink WSN are discussed. Figures 6(c) and 7(c) show the results in case of the multiple sink WSN and $q_i = 0.2$. As compared with Figures 6(a) and 7(a), chaos synchronization is broken down. Basically, each wireless sensor node is synchronized to the nearest sink node based on Equations (3) and (6). However, if a wireless sensor node has the same hop count to multiple sink nodes, the wireless sensor node is affected simultaneously by these sink nodes. These sink nodes are not synchronized to each other since they are not coupled via direct wireless communication. Hence, the wireless sensor node having the same hop count to multiple sink nodes cannot be synchronized to any sink nodes. It should be noted that it is hard also for the periodic SDGS to synchronize such wireless sensor nodes in the case of the multiple sink WSN. Figures 6(d) and 7(d) show the results in the case of the multiple sink WSN and $q_i = 0.6$. As compared with Figures 6(b) and 7(b), significant differences cannot be found.

Here, we consider wireless sensor nodes which relay sensor information to sink nodes. If all the wireless sensor nodes are synchronized to each other, sensor information must be relayed to the sink nodes without transmission errors. However, it is considered that many wireless sensor nodes relay the same sensor information. This problem becomes more serious if density of wireless sensor nodes increases, and the number of wireless sensor nodes and sink nodes increases. In the CDGS, a part of broken paths due to transmission errors can exist as wireless sensor nodes are quasi-synchronized. However, it should be noted that sensor information can be relayed to at least one sink node if at least one active path to the sink node exists.

In order to evaluate transmission efficiency in more detail, we evaluate the total number of relay wireless sensor nodes (TSN) which relay sensor information from a wireless sensor node to sink nodes. Also, we evaluate average delivery ratio (ADR) for sensor information from a wireless sensor node to sink nodes. As explained in Section 2, $t_r$ is a parameter
concerned with success of relaying sensor information. In the simulations, \( t_r \) is fixed to 1.8. We select 40 wireless sensor nodes \( S_k \) \((k = 1, \cdots, 40)\) allocated on the most outside of the left concentric circles shown in Figure 5. In the simulations, the following situations are considered.

- In each trial, only one wireless sensor node in \( S_k \) transmits sensor information, and the other wireless sensor nodes do not transmit own sensor information.
- Each wireless sensor node can not distinguish the same sensor information via plural paths from a transmitting sensor node, and may relay it more than once.
- Delivering sensor information is regarded as success if at least one sink node can receive the sensor information.

\( S_k \) transmits sensor information once in each self-firing timing. Then, TSN and ADR for 100 times transmissions are calculated.

Figure 8 shows distance levels of transmitting wireless sensor nodes \( S_k \). The horizontal axis denotes indexes of the transmitting wireless sensor nodes, where the indexes are sorted for their distance levels in the case of the single sink WSN. As the number of sink nodes increases, the nearest sink node of each wireless sensor node can change. Hence, for all the transmitting wireless sensor nodes, the distance levels in the multiple sink WSN must be smaller than or equal to those in the single sink WSN.

Figures 9 and 10 show TSN and ADR, respectively. The horizontal axis denotes indexes of the transmitting wireless sensor nodes, where the indexes are sorted for their distance...
levels in the single sink WSN. TSN and ADR change depending on the transmitting wireless sensor nodes. This is due to differences of the number of relay wireless sensor nodes to sink nodes and/or the number of transmission paths to the sink nodes. That is, this is due to network topology. In the case of the single sink WSN and \( q_i = -0.2 \), all the wireless sensor nodes are synchronized to each other as shown in Figures 6(a) and 7(a). Then, sensor information must be transmitted to the sink node without transmission errors as shown in Figure 10(a), however, the same sensor information is relayed by many wireless sensor nodes as shown in Figure 9(a). In the case of the multiple sink WSN and \( q_i = -0.2 \), synchronization of each wireless sensor node is broken down as shown in Figures 6(c) and 7(c). Then, TSN for each transmitting wireless sensor node deceases, compared with the case of the single sink WSN as shown in Figure 9(a). However, it should be noted that high ADR is kept in the most transmitting wireless sensor nodes as shown in Figure 10(a). This means that at least one active path from the transmitting wireless sensor nodes to either sink node is available with high probabilities. However, in some transmitting wireless sensor nodes, ADR decreases significantly.

In the case of the single sink WSN and \( q_i = 0.6 \), each wireless sensor node is synchronized partially and intermittently as shown in Figures 6(b) and 7(b). This result is the same also in the case of the multiple sink WSN and \( q_i = 0.6 \) as shown in Figures 6(d) and 7(d). Then, TSN can be reduced significantly as shown in Figure 9(b). It can contribute to energy consumption savings of each sensor node. Transmission errors of sensor information can occur due to quasi-synchronization of each wireless sensor node. However, it should be noted that high ADR is kept in all the transmitting wireless sensor nodes as shown in Figure 10(b).
Tables 1 and 2 show average, maximum and minimum values of TSN and ADR in all 40 transmitting wireless sensor nodes. These results show that partial and intermittent synchronization can reduce the number of relay wireless sensor nodes keeping high ADR. In this case, a part of broken paths due to transmission errors exists. However, sensor information can be relayed to at least one sink node if at least one active path to the sink node exists. In the case of the multiple sink WSN and \( q_i = -0.2 \), minimum value of ADR is the lowest. Because, if a wireless sensor node has the same hop count to multiple sink nodes, the wireless sensor node is affected simultaneously by these sink nodes, based on Equations (3) and (6). Then, the wireless sensor node can not be synchronized to any sink nodes. Therefore, ADR can decrease significantly as it transmits sensor information. Also, similar results can be found in the conventional SDGS. Hence, quasi-synchronization in the CDGS can realize more effective data gathering. In the simulations, all the wireless sensor nodes have the same parameters. If the parameters are set appropriately depending on the number of neighbor wireless sensor nodes and/or their distance levels, TSN and ADR can be improved more. We should consider such a parameter setting method in the future.

In order to compare the cases of the single sink WSN and the multiple sink WSN in more detail, we choose one transmitting wireless sensor node \( S_k \) as a representative example. \( S_k \) has distance level \( l_k = 4 \) in both the single sink WSN and the multiple sink WSN. In the case of the multiple sink WSN, \( S_k \) has the paths to both sink nodes. Only \( S_k \) is assumed to transmit sensor information 100 times. We then calculate the average number of relays of the sensor information in each relay wireless sensor node. Figure 11 shows the simulation results. It should be noted that the average number of relays in the case of the multiple sink WSN is distributed to more wireless sensor nodes as compared with that in the case of the single sink WSN. Especially, in the case of \( q_i = 0.6 \), great load balancing of each wireless sensor node can be realized. These results show that either path to multiple sink nodes can be effectively selected. It can contribute to prolonging WSN lifetime.

4. **Conclusions.** This paper has analyzed transmission efficiency of a chaos-based data gathering scheme using chaotic pulse-coupled neural networks. Through numerical simulations, we have shown that the proposed scheme can reduce the total number of the wireless sensor nodes which relay the same sensor information, keeping high delivery ratio. For prolonging the lifetime of wireless sensor networks, it is important that power supply of transceivers should be turned off when wireless sensor nodes do not transmit or relay sensor information, and the number of transmissions is reduced. In addition, the proposed scheme can be easily applied to wireless sensor networks with multiple sink nodes and
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Table 1. TSN and ADR for all 40 transmitting wireless sensor nodes

<table>
<thead>
<tr>
<th>Wireless sensor node index</th>
<th>$q_i = -0.2$</th>
<th>$q_i = 0.6$</th>
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<tbody>
<tr>
<td></td>
<td>Single</td>
<td>Multi</td>
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<tr>
<td>Average</td>
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(a) TSN  (b) ADR

Figure 11. Average number of relays of sensor information, (a) $q_i = -0.2$, (b) $q_i = 0.6$

shows great performances in the viewpoints of prolonging the lifetime of wireless sensor networks. Future problems include evaluation of energy consumption and comparison with periodic SDGS in more detail.

REFERENCES


