Bounding the Sensing Data Collection Time with Ring-based Routing for Industrial Wireless Sensor Networks

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Abstract

Industrial wireless sensor network (IWSN) exhibits data delivery time constraint from sensor node to sink node. The data delivery time in IWSN is unpredictable because of the dynamic routing and transmission collision in ad hoc networks. Considering the power consumption, the sensor node close to the sink node will incur substantial power consumption for data forwarding or data aggregation. This study adopts a proactive routing, which constructs the sensor nodes into a logical circular chain topology (i.e., ring topology), to avoid data collision problem and to bound sensing data collection time in IWSN. A load-balancing issue is considered to prolong the network lifetime. In this study, the construction of a logical circular chain is converted to the traveling salesman problem (TSP) with genetic algorithm to determine the load-balancing circular chain. Simultaneously, we use the linear programming scheme to model the logical circular chain construction. The simulated annealing algorithm is adopted to determine the optimal load-balancing chain. A ping-pong token mechanism is proposed to balance the residual power of each sensor node and to prolong the network lifetime. Simulation results reveal that the linear programming scheme with ping-pong token has the best data delivery time and system lifetime.

Keywords: Wireless sensor network, Linear programming, Simulated anneal algorithm, Load balance

1 Introduction

In recent years, wireless sensor networks (WSN) are extensively used in environment surveillance, factory surveillance [1-9], and ocean exploration [10-11]. In general, the sensor node in WSN is an embedded device with sensing and wireless interfaces. Moreover, all the sensor nodes are assumed to have fixed position and an unique identification. The sensor nodes are powered by battery with the same initial energy, and their transmitted power is fixed. The sensor node periodically senses the environment status and forwards this status to the sink node via wireless interface. Thereafter, the sink node forwards the collected sensing data to the controller via wire interface. The controller responds to the environment according to the received sensing data.

The data delivery in WSN is often performed by ad hoc routing because of the restricted communication range [12-13]. In the Destination–Sequenced Distance–Vector (DSDV), each mobile host periodically advertises its neighbor interconnection topology with other mobile hosts. Thus, each mobile host has the entire network topology and uses the shortest path routing for data transmission [14]. The reactive routing protocol of Ad hoc On-demand Distance Vector (AODV) is proposed for hosts in an ad hoc network [15]. To improve the network performance, authors in [16-17] used the multipath routing approach to efficiently utilize the available network resources. The path of the pair-wise directional geographical routing (PWDGR) considers node geographical information to make multipath to solve the problem in which the node energy near the sink node becomes evidently higher than that in the other nodes [18]. Considering the load balance and bandwidth aggregation, the directional geographical routing (DRG) makes multiple disjointed paths for real-time video streaming over WSN [19].

Data transmission time becomes unpredictable in ad hoc environment, which may incur signal collision problem. The fourth industrial revolution in manufacturing and industry (Industry 4.0) is valued and fascinating recently. An important issue is how to

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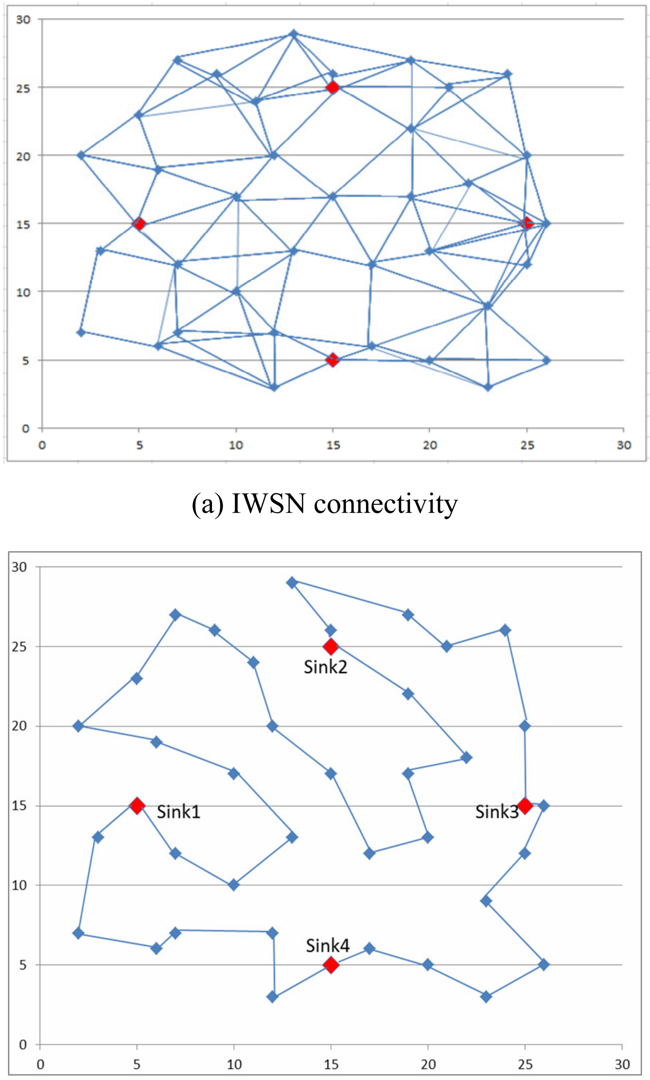
bound the sensing data collection time in industrial wireless sensor network (IWSN). To solve this problem, a Circular Chain Data Forwarding (CCDF) mechanism is proposed [20-21]. This mechanism constructs the sensor nodes in IWSN into the logical circular chain (i.e., ring-based routing) and applies token-based medium access control to avoid data collision problem. The concept of CCDF is illustrated in Figure 1, in which the blue node is the sensor node that relies on the battery to provide power and only has a wireless interface. The red node is the sink node that has a power line, wireless interface, and wired interface to connect with a controller. The directly connected nodes of node i is defined as the nodes that can directly receive the node i signal based on the wireless signal transmission power. Thus, the controller can obtain complete network connectivity topology by using the neighbor discovery technique to collect the neighbor discovery results of each sensor node (see Figure 1(a)). The controller can construct the network topology into the logical circular chain based on the network connectivity topology (see Figure 1(b)). In IWSN, the logical chain may consist of many sub-chains. Each sub-chain is defined as a path from a sink node to its neighboring sink node. Four sub-chains are shown in Fig. 1(b). On a token-based medium access control (MAC), the controller periodically issues a token to sink 1. The sink 1 passes the token to its next node in a clockwise direction. Once the token returns to the sink 1 position, sink 1 discards the token and waits for the new token to be issued by the controller. In the token-based MAC, the node will only transmit the packet when it has a token.

CCDF did not consider load balance among sub-chains, that is, the number of nodes in each sub-chain is unbalanced, long sub-chain incurs substantial power consumption, and time variance is compared with the short sub-chain in sensing data collection. This study targets the load-balancing logical circular chain construction to bound the sensing data transmission delay and to prolong the network lifetime.

This study proposes two logical circular chain construction schemes. These schemes are the traveling salesman problem (TSP-based) [22-24] and linear programming (LP-based), which are combined with the genetic algorithm (GA) [25] and simulated annealing (SA) algorithm [26], respectively. The SA algorithm is used to determine the optimal or near optimal solution of the linear programming model. In addition, a Ping-Pong token mechanism is proposed for the ring transmission to balance the residual power for each sensor node and to prolong the system lifetime.

The rest of this paper is organized as follows. Section 2 introduces the genetic algorithm with heuristic algorithm in the TSP-based method to construct a load-balancing logical circular chain. Section 3 introduces the linear programming model for the construction of the load-balancing circular chain. Section 4 presents the performance comparison among the different schemes. Finally, Section 5 provides a brief conclusion.



(a) IWSN connectivity

(b) Virtual circular chain

Figure 1. Virtual circular chain for IWSN

2 Logical Circular Chain Construction by TSP-based Load Balancing

The constructed logical chain starts from a sink node and loops back to the same sink node (see Figure 1(b)). All these nodes, including the sink and sensor nodes, must be visited only once. Thus, the virtual circular chain construction of IWSN can be transformed to TSP [21-23]. In TSP, a network G can be represented as {N, L}, where N is the set of cities and L is the distance set between any two neighbor cities. TSP is defined as starting from the selected city; thereafter, all cities N-1 will need to be visited before returning to the starting city. This process presents $(n-1)!/2$ choices. The objective of TSP is to determine the shortest route to visit each node once.

GA is used to determine the optimal or near optimal solution to solve the TSP problem because TSP is an non-deterministic polynomial-time hard (NP-hard) problem.

To consider the load-balancing in the virtual circular chain construction, a balance index derived by [5], which is similar to Eq. (1), is used as the fitness value in GA.

$$LBI = \frac{(\sum B_i)^2}{(n\sum B_i^2)} \quad (1)$$

where B_i is the length of the sub-chain i and n is the number of sub-chains. In this formula, the sub-chain length is defined as the number of nodes in the sub-chain. In Eq. (1), if the *LBI* value is near 1, then the constructed logical circular chain is balanced.

GA is shown in Figure 2. First, we randomly generate a thousand initial population (path) and calculate the fitness value for each path. The best 40 paths based on fitness value are selected for GA.

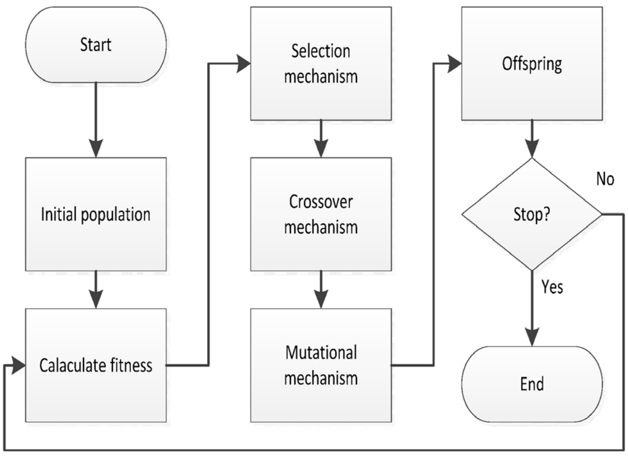


Figure 2. Genetic algorithm flowchart

Thereafter, we also randomly select 2 paths, denoted as F_path and M_path, from the first 40 paths to serve as parent. The nodes in the path are numbered in proper sequence.

In the crossover stage, a number i is randomly selected (i is less than or equal to the number of nodes). The node with node number i in the F_path is denoted as F_path[i]. We first search the location of the node M_path[i] in the F_path and assume that this location is j. Thus, we exchange the nodes between the F_path[i] and F_path[j] for a crossover operation in the F_path if these two nodes can be exchanged according to their connectivity. In the M_path, we perform the same crossover operations. We repeat the crossover process four times in the crossover stage.

In the mutation stage, the mutation is defined as whether to do the 5th crossover process or not with 0.8 probability. Finally, we derive two new offsprings. We add these two new offsprings into the selected 40 paths and maintain the first 40 paths according to the fitness value. In this study, the iterations from the crossover to mutation process are 2000 times.

3 LP-based Chain Construction

The virtual logical circular chain construction, which is modeled to a min–max integer linear programming (LP-based), is employed in this study. The formulation is described as follows.

Given Parameters:

D={1, 2, …, m}: Index set of original destination (OD) pairs. The OD pair comprises sink nodes, that is, the path of an OD pair is a sub-chain. Hence, we assume that the location and sequence of the sink nodes are known.

N={1, 2, …, n}: Index set of nodes that includes the sensor and sink nodes.

L: Index set of logic links. $(i, j) \in$L means a direct connectivity exists between nodes j and i.

C_{ij}: Cost of link (i, j).

Decision Variables:

x^d_{ij}: Binary variable. If this value is 1, then the link (i, j) is selected in the routing path of the OD pair d, $d\in$D; otherwise, this value is 0.

u_k: Slack variable to prevent multiple logical circular chains. $k\in$N.

Objective Function:

$$\text{obj: min } z \quad (2)$$

Subject to:

$$\sum_{\{j:(i,j)\in L\}} x^d{}_{ij} - \sum_{\{j:(j,i)\in L\}} x^d{}_{ji} = \begin{cases} 1, & \forall \text{i} = \text{source node} \\ -1, & \forall \text{i} = \text{destination node} \\ 0, & \text{else} \end{cases} \quad (3)$$

$$\sum_{d\in D}\sum_{\{j:(i,j)\in L\}} x^d_{ij} = 1, \forall \text{i} \in \text{N} \quad (4)$$

$$\sum_{d\in D}\sum_{\{j:(j,i)\in L\}} x^d_{ji} = 1, \forall i \in \text{N} \quad (5)$$

$$\sum_{(i,j)\in L} c_{ij}x^d_{ij} \le z, \forall \text{d} \in \text{D} \quad (6)$$

$$u_i - u_j + nx_{ij} \le n-1,\ 2 \le i \ne j \le n \quad (7)$$

$$x^d_{ij} \in (0/1)\ ,\ d \in D\ ,\ (i,j) \in L\ ,\ u_k \ge 0\ ,\ k \in \text{N} \quad (8)$$

The flow conservation law is used to determine a route for each OD pair in Constraint (3). Constraints (4) and (5) require that all nodes have to be visited and should only be visited once. The maximum length among all sub-chains is not greater than variable z in Constraint (6). This is used to determine the highest sub-chain length and to combine with the object function to derive the load-balancing results. The objective function in (2) aims to minimize the value of z for the load-balancing chain construction. Constraint (6) is used to prevent multiple chains construction. Constraint (8) is an integer constraint.

The SA algorithm is applied to obtain the solution of the LP-based virtual circular logical chain construction, which has the ability to avoid the local minimum to determine the optimal or near optimal solution [7]. The pseudo code of the SA algorithm is shown in the following. Parameter T stands for the temperature and I is the number of iteration. We determine a neighbor solution in each iteration. If the energy E of the neighbor solution is lower than the current solution, then we update the current solution to the neighbor solution. Otherwise, we consider a probability to decide whether to update the current solution. Temperature T is reduced 0.999 times in every L iteration. In this case, the energy E of a solution is calculated as follows:

$$E = \underset{d \in D}{Max} \sum_{(ij) \in L} c_{ij} x_{ij}^{d} \quad \textbf{(9)}$$

```
procedure SA
begin
set_initia_order; best_order = current_order;
E^best =E(best_order) ; T=T^0;
while stopping_criterion not ture
  begin
    l = 0;
    while l < L do
      begin
        next_order = exchange_two_random_node (current_order);
        ΔE = E(next_order) − E(current_order);
        if ΔE ≤ 0 then
          begin
            current_order = next_order;
            if E(current_order) < E^best then
              E^best = E(current_order); best_order = current_order;
          end
        else if ranom(0,1) < e^(−ΔE/T) then
            current_order = next_order; l = l +1;
        end
        T = T × 0.9999;
  end
end {procedure}
```

Figure 4. Simulated annealing algorithm

4 Simulation Results

In this section, we use computer simulation to evaluate the proposed algorithm for the logical circular chain construction in IWSN. The sensor nodes in the simulation are randomly distributed in the 30 m × 30 m area.

First, we compare the performance of the SA algorithm with the Lingo tool to evaluate whether the former will be able to determine the optimal solution. Table 1 illustrates the comparison results. This table also shows the symbol OPT, which stands for Lingo optimal tool. In the environment of the 10 to 40 sensor nodes, the SA algorithm obtains the same results to the Lingo tool in a load-balancing index. This result proves that the SA algorithm can determine the optimal solution with limited computation time. In the 30 sensor nodes, the Lingo tool requires 62 minutes to determine the optimal solution. However, SA only takes 0.1 second to obtain the result. We only use the SA algorithm to solve large-scale problems to evaluate the results of the load-balance and system lifetime.

Table 1. Comparison between Optimization and SA

Number of sensors	*Load Balancing Index (LBI)*	
	SA	*OPT*
10	98%	98%
20	100%	100%
30	99%	99%
40	100%	100%

The simulated load-balancing against the number of sensor nodes among the CCDF, TSP-based, and LP-based schemes is shown in Figure 3. The LP-based scheme has the best load-balancing performance compared with the CCDF and TSP-based schemes in all sensor node numbers (see Figure 3).

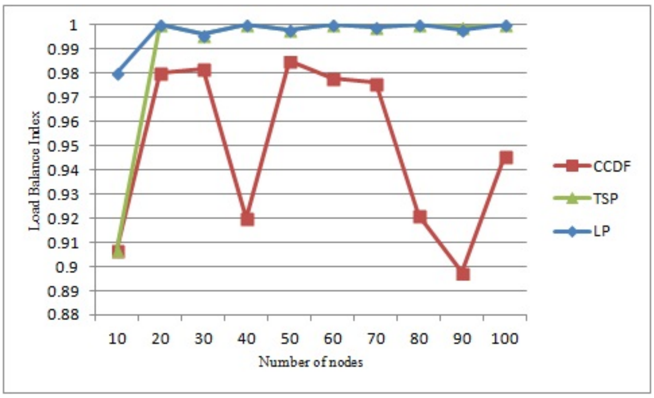


Figure 3. Comparison of the load balance index

In the Token-based mechanism, the controller issues a token to the sink node 1 periodically (see Figure 1). The virtual chain sequence indicates that the sink node 1 forwards the token to the next sensor node. Once a sensor node receives a data packet from its previous node, it aggregates the received data with self-sensing data and forwards the data packet to the next sensor node (if this node has a token). The data receiving, aggregation, and forwarding proceed one after the other until the process reaches the sink node. Thereafter, the sink node forwards the received data packet to the control, which also forwards the received token packet to the next node according to the construction chain.

To facilitate a unified comparison, the network lifetime is represented by the number of round that begins when the controller issues a token up to when the controller collects all the sensing data. In the Token-based mechanism, the chain is broken and the network fails as long as the power of one of the sensor nodes runs down. The network lifetime is the duration from the time that the controller issues the first token up to the time of network fail.

To evaluate the network lifetime, the radio energy dissipation model of a node used in the simulation is shown in Figure 4 [6]. The transmitter has energy dissipation in radio electronics and transmission power amplifier. The receiver dissipates energy to run the radio electronics. It considers the free space and multipath fading models. If the transmission distance $\boldsymbol{d}$ is less than the threshold $\boldsymbol{d_0}$, then the free space model (i.e., the d^2 power loss factor) is used. Otherwise, the multipath fading model (i.e., the d^4 power loss factor) is used. The energy dissipation for transmitting an l-bit message in a distance d is shown in Eq. (10) and the required power to receive this message is shown in Eq. (11).

$$E_{Tx}(l,d) = E_{Tx-elec}(l) + E_{Tx-amp}(l,d) = \begin{cases} lE_{elec} + l\varepsilon_{fs}d^2, d < d_0 \\ lE_{elec} + l\varepsilon_{mp}d^4, d > d_0 \end{cases} \quad \textbf{(10)}$$

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \quad \textbf{(11)}$$

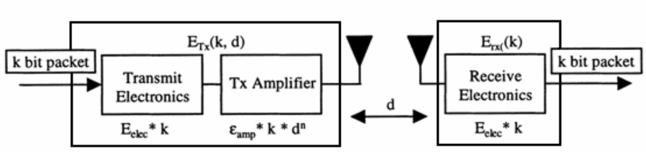


Figure 4. Radio energy dissipation model

$\boldsymbol{E_{elec}}$ represents the electronics energy of the digital coding, modulation, filtering, and spreading of the signal. $\boldsymbol{\varepsilon_{fs}}$ and $\boldsymbol{\varepsilon_{mp}}$ represent the amplifier energy. In this study, $\boldsymbol{E_{elec}}$, $\boldsymbol{\varepsilon fs}$, and $\boldsymbol{\varepsilon_{mp}}$, are set to 10 nJ/bit, 10 pJ/bit/m^2, and 0.0013 pJ/bit/m^4, respectively.

Figure 5 plots the network lifetime against the different sensor node numbers among the CCDF, TSP-based, and LP-based schemes. The LP scheme enjoys the highest network lifetime than the others (see Figure 5). Thus, the load-balancing consideration can effectively prolong the network lifetime. Moreover, if the number of sensor nodes increase as the number of sink node is fixed, then the sub-chain length is large. Thus, the network lifetime decreases rapidly.

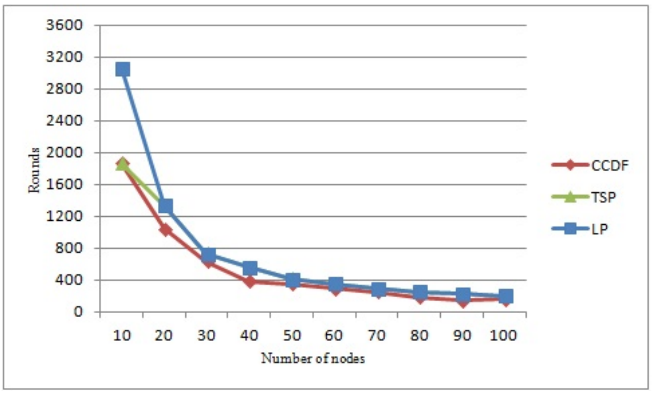


Figure 5. Network lifetime in the different number of nodes

Figure 6 illustrates the network lifetime against the different sensor node numbers in the fixed number of node to number of sink ratio. Hence, the ratio is fixed at 10:1. The LP- and TSP-based schemes, which consider the load-balancing chain construction, have better results than that of CCDF (see Figure 6).

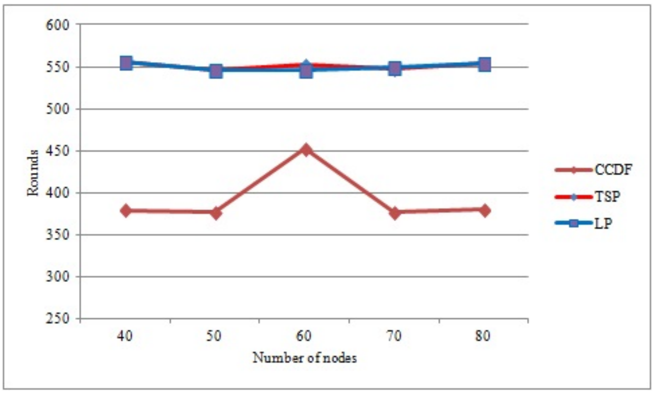


Figure 6. Network lifetime in the same ratio of node to sink

We evaluate the sensing data collection time, which is the duration from the time the controller issues a token to the time the controller receives all the sensing data. In our environment, we assume that the sink node has wireless and wired network interfaces. This node uses wireless interface to communicate with the sensor nodes and relies on wired interface to communicate with the controller. Thus, once the sink node receives the sensing data, it can forward the received sensing data to the controller via the wired network interface.

The time delay in a sensor node is defined as follow:

$$T_i = T_{ov} + i \times s_t, , \quad \textbf{(12)}$$

where i is the sensor node sequence index in the associated sub-chain. The value T_{ov} is the constant overhead for the protocol header processing and s_t is the transmission time of one sensing data unit. The i'th sensor node aggregates the previous (i-1) node's sensing data with the self-sensing data because of data aggregation to form a packet and forward to the next sensor node. Thus, the total packet transmission time is $i \times s_t$ for node i.

The data collection time (DCT) for a sub-chain is as follows:

$$DCT = \sum_{i=1}^{n} T_i = \sum_{i}^{n} (T_{ov} + i \times s_t). \quad \textbf{(13)}$$

We compare the proposed algorithm with the TSP-based and CCDF schemes to observe the maximum traversal time of the sub-chains (see Figure 7). When the number of nodes is 90, the LP-based scheme saves 55% traversal time than CCDF (see Figure 7). This result means that if we construct a load-balancing circular logic chain, then it is able to minimize the maximum sub-chain length. Thus, the maximum traversal time of a sub-chain can be significantly reduced.

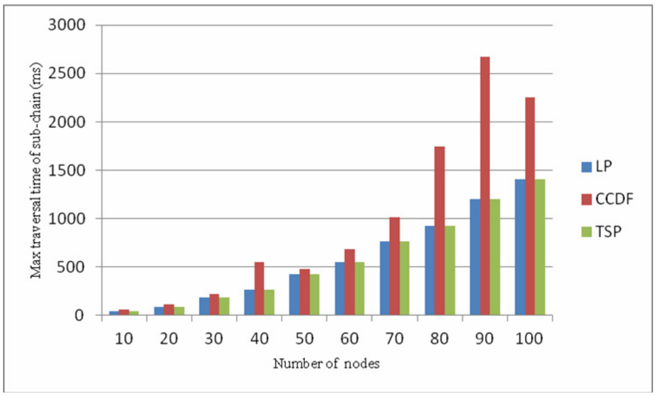


Figure 7. Maximum traversal time of a sub-chain

In the Token-based delivery mechanism, the amount of transmitted data depends on the location of a node in a sub-chain. If a node is located at the end of a sub-chain, then this node needs to forward other data for its previous nodes. Thus, this particular node consumes substantial power. This phenomenon indicates that the scheme has unbalanced power consumption in each node. To solve this problem, we propose a Ping-Pong Token-based delivery scheme. In this scheme, the controller initially issues a token in a clockwise direction and then issues a token in the counterclockwise manner the next time, and vice versa. Each node transmits and receives the same amount of data on average based on this scheme. Therefore, the power consumption in each node can be balanced.

Figure 8 compares the Token- and Ping-Pong Token-based schemes in terms of network lifetime. The results show that the latter has significantly improved the network lifetime in all cases. Figure 9 depicts the comparison of network lifetime in the different number of nodes with different mechanisms. When the number of sensor nodes is 40, the Ping-Pong Token with LP-based scheme can prolong 95% of the network lifetime than CCDF.

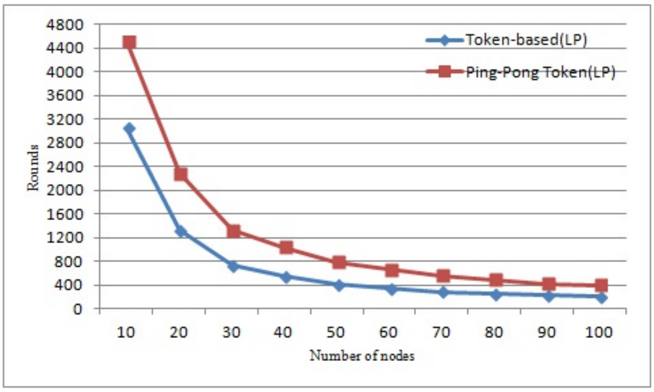


Figure 8. Comparison of the network lifetime in the Token- and Ping-Pong Token-based schemes

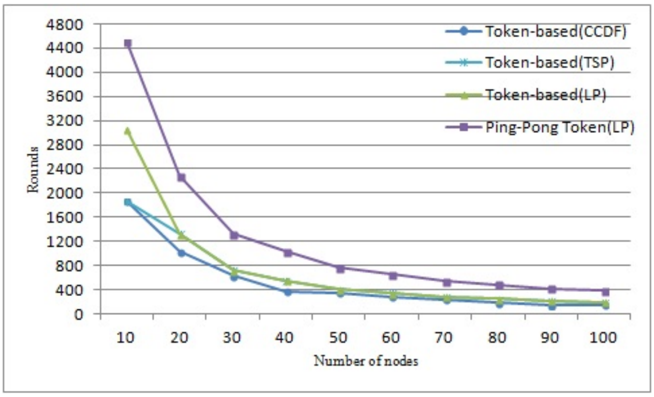


Figure 9. Comparison of the network lifetime in the different mechanisms

We also took a snapshot of the residual energy in each node once one of the nodes has consumed all of its energy under the 40 nodes condition (see Fig. 10 for the results). Accordingly, the Ping-Pong Token scheme is able to balance the power consumption in each node (see Fig. 10).

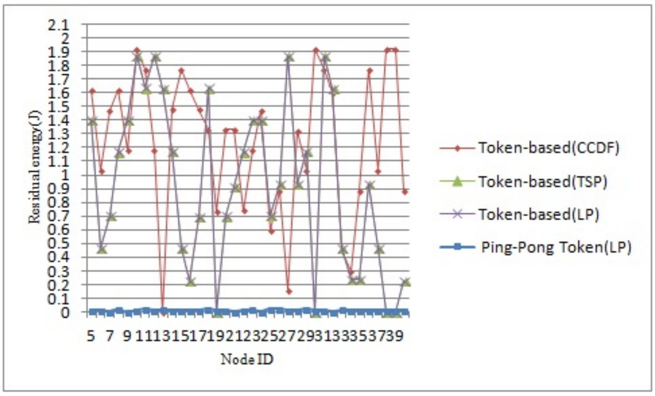


Figure 10. Residual energy of each node

5 Conclusion

This study constructs a virtual load-balancing circular chain in IWSN to resolve the transmission time constraint. This method also aims to reduce and balance the power consumption to prolong the network lifetime. The virtual balanced chain construction is converted to the TSP problem and is modeled by the min–max linear programming problem. The SA algorithm is adopted to solve the min–max optimization problem. The simulation results reveal that the LP-based scheme can achieve load-balancing chain construction and gain improved results in terms of power consumption and network lifetime. In addition, a Ping-Pong Token scheme is proposed to achieve substantial balanced power consumption in each sensor node to prolong the network lifetime. Combined with the LP-based scheme, the Ping-Pong Token scheme prolongs 95% of the network lifetime than CCDF in the 40 sensor nodes condition.

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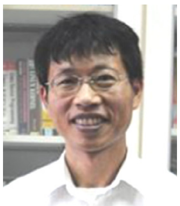
Biographies



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