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A New Hybrid Architecture with an Intersection-Based Coverage Algorithm in Wireless Sensor Networks

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Abstract. Energy is limited in wireless sensor networks (WSNs) so that energy consumption is very important. In this paper, we propose a hybrid architecture based on power-efficient gathering in sensor information system (PEGASIS) and low-energy adaptive clustering hierarchy (LEACH). This architecture can achieve an average distribution of energy loads, and reduced energy consumption in transmission. To further extend the system lifetime, we combine the intersection-based coverage algorithm (IBCA) with LEACH architecture and the hybrid architecture to prolong the system lifetime that introducing sensor nodes to enter sleep mode when inactive. This step can save more energy consumption. Simulation results show that the performance of our proposed LEACH architecture with IBCA and the hybrid architecture with IBCA perform better than LEACH architecture with PBCA in terms of energy efficiency, surviving nodes and sensing areas.

Keywords: Hybrid architecture, PEGASIS, LEACH, System lifetime, IBCA, PBCA.

1. Introduction

Wireless sensor networks (WSNs) [1] are typically consist of a large number of resource-constrained sensor nodes which are randomly scattered to collect environmental condition data from an area [2], [3], such as humidity, temperature, solar radiation, concentration of carbon dioxide [4], and risky places for humans. Each sensor node is able to independently manage operations [5] and deliver the data to a base station (BS) by radio wave, infrared rays, or optical fiber transmission [6]. The lifetime of a node is dependent on its energy consumption rate in WSNs. Because the sensors are usually located in dangerous or inaccessible areas, and the battery cannot be replaced. The control of energy efficiency is a primary issue [7], [8], [9] in WSNs.

A Low-energy adaptive clustering hierarchy protocol (LEACH) for a distributed network proposed by Heinzelman et al. [10]. Sensor nodes are divided into several clusters in the LEACH architecture. Each cluster choosing a sensor node as the cluster head (CH), which delivers an advertisement (ADV) to every neighboring sensor node in accordance with carrier-sense multiple access (CSMA) [11], [12], [13] protocol in the MAC layer. Each sensor node identifies itself as cluster member with the CH [14], [15] through the strength of the ADV message. Cluster members transmit data to the CH using the time division multiple accesses (TDMA) [12], [13] mechanism. This TDMA protocol enables mechanisms to avoid and resolve collisions, because TDMA has a designated time slot for each node in which only that particular node transmits. Finally, the CH transmits the data to the BS which performs data aggregation.

In power-efficient gathering in sensor information system (PEGASIS) architecture [16], the nodes transmit data to the next closest neighboring nodes, and receive data from previous closest neighboring nodes, with all of the sensor nodes based on the greedy algorithm, to form a connected chain; each node collects from the previous node and transmits to the next one, until the node closest to the BS, called the chain header, is reached; it performs data aggregation and transmission to the BS [16], [17], [18]. The role of chain header for each round will rotate between nodes.

There are two problems with LEACH. First, there is an excess of CHs. Second, the distance between the CHs and cluster nodes is too great. However, PEGASIS architecture also has problems. In the first place, the transmission distance may not be the shortest between sensing nodes. Next, the aggregated number of data packets is larger than in LEACH architecture. To overcome these problems, we developed a combined architecture based mainly on PEGASIS, but utilizing the advantages of the LEACH structure.

In WSNs, sensor nodes are randomly deployed, as a result, the sensor field is uneven density, and this will cause coverage issues [19]. If a node's sensing range is overlapped, it is called a redundant node. The redundant node is entered into sleep mode, which does not affect the overall sensor field or connectivity. Sleep mode is a way to prolong the network lifetime. In order to upgrade LEACH system performance, there is a phase-based coverage algorithm (PBCA) [20], [21] for locating all redundant nodes. The results of LEACH architecture with PBCA show that provides excellent system efficiency compared with the original LEACH architecture. On the other hand, an intersection-based coverage algorithm (IBCA) is proposed in [22], [23], that is capable of locating all redundant nodes. The number of redundant nodes of IBCA will be larger than that of PBCA. Thus, IBCA can improve the network lifetime more than PBCA.

In order to achieve better network performance, we propose novel schemes involving the application of IBCA to the LEACH [24] and hybrid architectures in this paper. Our schemes can identify redundant nodes to improve energy consumption.

The rest of this paper is organized as follows: Section 2 describes the IBCA. In Section 3, we combine of IBCA and the LEACH architecture. Section 4 introduces our proposed hybrid topology architecture, and the combination of IBCA with the hybrid architecture. In Section 5, we simulate and analyze LEACH, LEACH with PBCA, LEACH with IBCA, and the hybrid architecture with IBCA that compare the performance of four architectures. The last section is the conclusion of this paper.

2. Related Work

PBCA [20], [21] is employed as a criterion to determine whether the target node is k-coverage. PBCA is utilized to identify whether the sensing range of target node is fully covered by neighbor nodes with a time complexity $O(N \log N)$, where N represents the number of neighbor nodes around the target sensor node.

IBCA [22], [23] uses intersections to judge if certain sensor nodes can enter sleep mode. Both intersections of a target sensor node's sensing range and other nodes' sensing ranges and intersections on the perimeter of the total sensing range, are k-coverage. The result is that the target sensor node will be k-coverage. This algorithm requires the coordinate information of all sensor nodes and the computational complexity is $O(N^3)$, where N is the number of neighbors of the target sensor node. Figure 1 shows an intersection of two sensor nodes. The target sensor node p_y and the neighboring sensor node p_x will intersect at two points, which are intersection 1 and intersection 2.

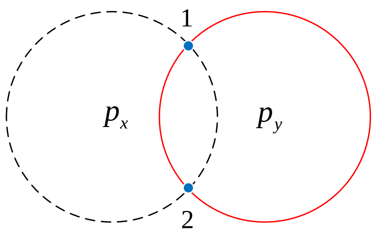

Fig. 1. The intersection of sensing ranges

The IBCA has a wider judgment condition ($d < 2R_s$) than the PBCA [20], [21], where d is the distance from a sensor node to the target sensor node, R_S is the sensing range of each sensor node. Therefore, the selected number of redundant nodes will be larger than that of PBCA. The number of redundant nodes that can be used for judgment will be larger. In other words, there are more neighbor node of the target sensor node that can be used for judgment. The calculation will become more complicated, and the implementation time will become longer.

IBCA provide redundancy rules for nodes as shown in [22], [23]. If both conditions have been established, the target node p_y is considered a redundant node. Assuming a set of overlapped neighbor nodes $N(p_y)$, neighbor nodes $p_x \in N(p_y)$, and d is the distance from neighbor node p_x to target node p_y.

Condition 1. The distance from p_x to p_y should be less than or equal to twice the sensing range R_S. We have as follows:

$$d(p_y, p_x) \le 2R_S, \forall p_x \in N(p_y) \quad (1)$$

Condition 2. The intersections are generated by node p_y and its neighbor nodes p_x.The target node p_y must check all the intersections within its sensing range. Each intersection overlaps coverage by each neighbor node's sensing range at least once.

It is a redundant node which can enter sleep mode which intersections of a sensor node p_y are covered by other sensor nodes' sensing ranges.

LEACH has two point problems. One is generate the excess of CHs. Another is distance between the CHs and cluster nodes. However, PEGASIS architecture has one problem that the aggregated number of data packets is larger than in LEACH architecture. To improve above problems, we proposed a combined architecture mainly based on PEGASIS, but utilizing the advantages of the LEACH architecture.

Our proposed architecture has two advantages. One is using PBCA to identify the sensing range of target node is fully covered by neighbor nodes. Another is using IBCA to find the redundancy nodes, and then let these nodes get into sleep mode.

3. LEACH Architecture with Intersection-Based Coverage Algorithm

In this section, we combine IBCA with LEACH topology architecture [10] and enter redundant sensor nodes into sleep mode. In this way, we improve system energy efficiency and extend the system lifetime.

3.1. The LEACH Architecture

In [10], Heinzelman et al. proposed the LEACH architecture operation. Each cluster member delivers data directly to the cluster head, rather than to the distant base station. As a result, the energy consumed by the cluster members is merely the amount required during data transmission between cluster members and the cluster head, although the cluster head requires a larger amount of energy to perform data aggregation and implement data transmission to the base station. It should be noted that in LEACH architecture, the system is composed of variable clusters for each round.

LEACH protocol is mainly divided into two phases. The first is the setup phase; there is a probability $P_i(t)$ that each sensor node will be specified as the cluster head in the initial round. The average expected value of the cluster head number is given by:

$$E[CH] = \sum_{i=1}^{K} P_i(t) \times 1 = \alpha \qquad (\mathbf{2})$$

Where $E[CH]$ is the average expected value of the number of cluster heads, K is the total deployed number of sensor nodes in a WSN, $P_i(t)$ is the probability that node i will decide it is to become a cluster head at time t and α is the cluster quantity.

In order to prevent nodes serving as a cluster head in consecutive rounds, (3) determines the probability that each node will become the cluster head:

$$P_i(t) = \begin{cases} \dfrac{\alpha}{K - \alpha \times (r \bmod \dfrac{K}{\alpha})} & , C_i(t) = 1 \\ 0 & , C_i(t) = 0 \end{cases} \quad \textbf{(3)}$$

Where r is the current round and t is increased by unity in the event that all the cluster members have acted as the head. $C_i(t) = 0$ indicates that node i has been the cluster head this round. $C_i(t) = 1$ indicates that a node has not yet been the cluster head this round. LEACH architecture requires that each cluster member serve as the head once for each K/α round. Each node i should choose to become a cluster head with probability $P_i(t)$ at round r.

3.2. The LEACH Architecture with IBCA

To extend the system lifetime, we combine the LEACH architecture with IBCA [24]. First, we use IBCA to find the redundant sensor nodes whose intersections are covered by other nodes' sensing ranges. Let these redundant sensor nodes enter sleep mode in order to reduce the energy consumption of the WSN. The remaining nodes of the WSN then form LEACH architecture. The flow chart is shown in Fig. 2.

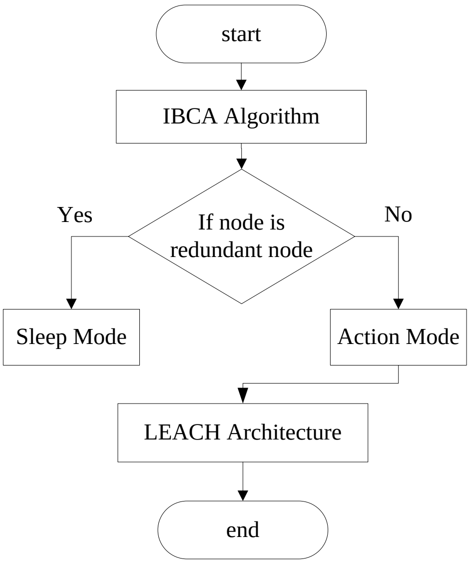

Fig. 2. The flow chart of LEACH architecture with IBCA

4. An Intersection-Based Coverage Algorithm for the Novel Hybrid Architecture

In this paper, we propose novel hybrid architecture with IBCA in order to obtain the advantages of both the PEGASIS and LEACH architectures. The hybrid architecture combined with IBCA improves the system energy efficiency and extends the system lifetime.

4.1. Our Novel Hybrid Architecture

In our proposed method, the hybrid architecture appoints a sensor node nearest the BS in each round, called the leader. The leader is responsible for the final aggregated data transmission to the BS. The leader is selected in turn from all the sensor nodes, so as to prevent the premature death of any one leader. When all of the sensor nodes have served as the leader, a new round begins.

The BS implements algorithms and receives data from sensor nodes. It has a leader list L which records the status of all the sensor nodes that have served as the leader. Those nodes that have been appointed leader this round and dead nodes will be removed from this list. After deleting the deceased nodes and former leaders, the BS designates the node closest to the BS as the current leader. If two or more sensor nodes are the same distance from the base station, the node with the highest energy will serve as leader. The purpose of this selection is to update leaders; the leader list composed of all active nodes is updated after all the nodes have served as leader once each round.

After determining the leader, our new network architecture begins operating. The leader is defined as the only member in level 0. To illustrate this idea by levels, the members of level k are generated by members in level $k-1$. For example, the members in level 1 are determined by the ADV message in level 0. Define a set C_k composed of all the members in level k. The m^{th} member in level k is p_k^m, and $N(p_k^m)$ are all the non-level sensor nodes regarding p_k^m. Therefore, p_0^1 denotes the leader. Assuming the current level is level i, all the members of level i will send an ADV message consisting of an ID and a level number to members not of that level. Based on the strength of the received ADV message, members then determine if they belong to $N(p_k^m)$.

To show the details of how the transmission path is determined, define p_i as the i^{th} non-level node. The distance between nodes p_i and p_j is $d(p_i, p_j)$. The non-level nodes merely receive the ADV message to be sent by p_k^m.

As long as either of the criteria, which are $d(p_j, p_k^m) < d(p_i, p_k^m)$ or $d(p_j, p_k^m) < d(p_i, p_j)$, are satisfied, these nodes will become members of the next level.

For example, assume all members of level k have been found. Next, confirm a member from all the level $k+1$ members, which are known as pertaining to members in level k. Given two nodes p_i and p_j, both p_i and p_j belong to $N(p_k^m)$. Based on the above criteria, one of the conditions is established, then p_j is identified as a member in level $k+1$. It is clear that node p_j is closer to p_k^m than the other node.

As shown in Fig. 3, p_k^m represents the m^{th} member in level k, and is intended to locate the members belonging to level $k+1$ from among nodes p_a, p_b, p_c, p_d and p_e. Since all these non-level nodes merely receive the ADV message sent by p_k^m, nodes p_a, p_b, p_c, p_d and p_e all pertain to $N(p_k^m)$, that is, $N(p_k^m)=\{p_a, p_b, p_c, p_d, p_e\}$. According to the time interval between the transmission and reception of the ADV message, it is discovered that $d(p_c, p_k^m)$, as well as $d(p_d, p_k^m)<d(p_e, p_k^m)$, and then $d(p_e, p_c)$, as well as $d(p_e, p_d)>d(p_e, p_k^m)$. For the first criterion, $d(p_d, p_k^m)<d(p_e, p_k^m)$ is satisfied; then node p_d is identified as a member of level $k+1$ in the same manner. For the second criterion, $d(p_e, p_d)>d(p_e, p_k^m)$ is satisfied, and then p_e is identified as a member of level $k+1$ in the same manner.

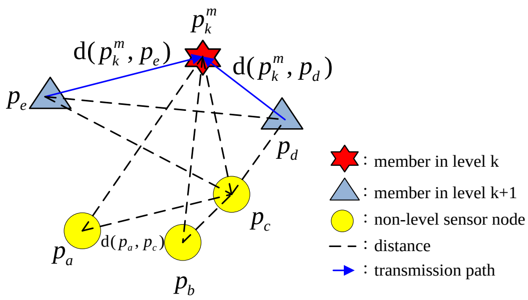

Fig. 3. Determination of data transmission path between nodes

Applying such criteria to node p_a, we find that $d(p_c, p_k^m)$, $d(p_d, p_k^m)$, $d(p_e, p_d)<d(p_a, p_k^m)$ and then $d(p_a, p_c)<d(p_a, p_k^m)$. It is concluded that p_a does not pertain to level $k+1$, for neither of the two criteria are satisfied. Similarly, p_b and p_c are both identified as non-members of level $k+1$.

Fig. 4 illustrates the node distribution in which p_b is the leader, the only member in level 0, while nodes p_a, p_c, p_e and p_h are members, located by $p_b=p_0^1$, in level 1. Likewise, nodes (p_f, p_d, p_g, p_i, and p_l), (p_j, p_k, p_m, p_o, and p_n), (p_r, p_q, and p_p) and p_s are members in levels 2, 3, 4 and 5, respectively. The absence of a linkage message in response to the ADV message, sent by level members, represents the completion of the network configuration.

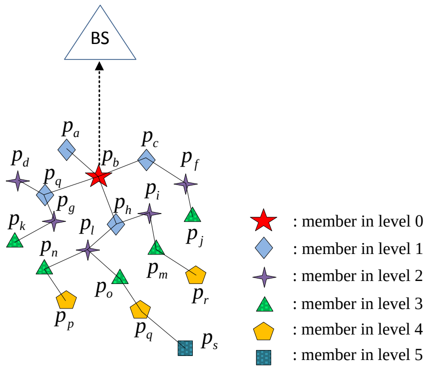

Fig. 4. The novel hybrid architecture

4.2. The Hybrid Architecture with IBCA

In this section, we propose the application of the IBCA [22], [23] to our hybrid architecture. The complete IBCA as given by:

program IBCA algorithm
  Parameter definition:
    S as the set of the sensor nodes entered into sleep mode;
    A as the set of the sensor nodes in active mode;
    L as the set of live sensor nodes;
    $Node$ as the number of live sensor nodes;
    $N(p_i)$ as the set of neighbor nodes of the target sensor node;
    $D(p_i)$ as the set of the intersections of p_i and $N(p_i)$ where $D(p_i)$ must be overlapped by other sensor node at least once;
  begin
    All the live nodes belong to A;
    repeat
      Locate $N(p_i)$, where $p_i \in L$, $N(p_i) = \{p_j \mid d(p_i, p_j) \leqq 2R_s\}$, $p_i \neq p_j$, $p_j \in L$, and $p_j \in A$;
      Compute the intersections of p_i and neighbor nodes, where $p_j \in N(p_i)$;
      if p_i is permitted to enter sleep mode.
        $D(p_i)$ is an empty set;
        p_i is a redundant node permitted to sleep;
        $p_i \in S$;

```
      else
         p_i remain active;
         p_i ∈ A ;
      end if
      i++ ;
   until i = Node
end.
```

First, we use the IBCA to find the redundant sensor nodes. Next, these redundant sensor nodes enter sleep mode in order to reduce the energy consumption of the WSN. We then set up the hybrid architecture with the active sensor nodes using IBCA. In our algorithm, all the sensor nodes can be divided into two modes: active mode or sleep mode. Therefore, the fewer nodes that are active, the lower the energy consumption for each round will be.

In our hybrid architecture, each sensor node has the functions of data detection, collection and transmission. A sensor node will send its own data to its neighbor node closest to the BS. The neighbor nodes will then perform data collection on the received data and their own detected data. After fusing the data, they will transmit the fused data to the neighbor node closest to the BS. This process will repeat until the data reaches a node with no sensor node closer to the BS than itself, and complete data will then be transmitted to the BS.

In order to extend the network lifetime, the IBCA for the hybrid architecture can be divided into three steps: active node selection, leader node selection and hybrid architecture.

Active node selection. The system will select sensor nodes to be active nodes using the IBCA, and instruct redundant sensor nodes to enter sleep mode.

Leader node selection. The system will compare the residual energy of each sensor node in the hybrid architecture and select the active sensor node with the maximum remaining energy as the leader.

Implementing hybrid architecture. The members of levels should send an ADV message to non-level nodes, and then a linkage message is sent to the remainder of those non-level nodes. The ADV messages of the linkage contain their identification, the members pertaining to the next level and the reception time. There are two criteria for judging if the condition is satisfied for them to be members of the next level. This ADV message is a small message which includes the node’s ID and a header, defined as an announcement message. This determines which non-cluster head node must join which cluster in this round, according to the signal strength of the ADV message from each CH.

Once members of the level have sent the ADV message until it does not contain any linkage message, the WSN configuration is complete. Fig. 5 shows the flow chart of the hybrid architecture with IBCA.

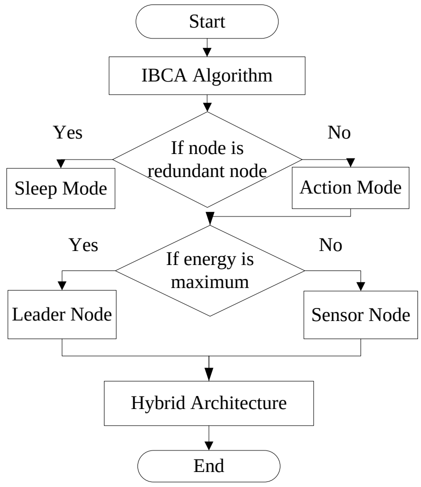

Fig. 5. The flow chart of our hybrid architecture with IBCA

5. Simulation Results

We propose LEACH with IBCA, and hybrid architecture with IBCA in this paper. In this section, we use C programming language to simulate and compare the system efficiencies, which are LEACH architecture [10], LEACH architecture with PBCA [21], LEACH architecture with IBCA and the hybrid architecture with IBCA. We compare the system efficiencies, which are based on total residual energy, number of deceased nodes and total sensing area. The simulation assumed 100 sensor nodes randomly distributed over a 100 meter by 100 meter field, a sensing radius R_S of 15 meters and BS located at (50, 150), with the parameters specified in Table 1. From [10], [25], the optimal cluster number k_{opt} is employed in the LEACH architecture. The transmission for energy consumption is given by:

$$E_{Tx}(l,d) = \begin{cases} l \times (E_{elec} + \varepsilon_{fs} \times d^2), & d < d_0 \\ l \times (E_{elec} + \varepsilon_{mp} \times d^4), & d \geq d_0 \end{cases} \tag{4}$$

Where $E_{Tx}(l,d)$ is the transmission of energy that packet size is l and the distance is d ; E_{elec} is the electronics energy; d_0 is distance threshold; ε_{fs} and ε_{mp} represent the amplifier energy of free space and the amplifier energy of multi-path, respectively. The receiving for energy consumption $E_{Rx}(l)$ is defined as:

$$E_{Rx}(l) = l \times E_{elec} \tag{5}$$

Figure 6 shows the total residual energy each round for four architectures. Our novel hybrid architecture with IBCA and LEACH architecture with IBCA obtained a large total residual energy in each round. The original LEACH architecture has the lowest residual energy, owing to the absence of IBCA. In addition, the LEACH architecture with IBCA has greater residual energy than does LEACH architecture with PBCA because IBCA can select more sensor nodes to enter sleep mode than PBCA can. The main reason for this is that the number of sensor nodes that can be used for judgment will become greater. Finally, the reason for the largest total residual energy is that our hybrid architecture ensures a minimum transmission distance between nodes.

Table 1. Simulation Parameter

Variables	Value
Initial energy	$E_{init} = 0.25$ J
BS location	(50,150)
Number of package	$l = 4000$ bits
Electronic energy	$E_{elec} = 50$ nJ/bit
Energy consumed in data fusion	$E_{DA} = 5$ nJ/bit/signal
Amplifier energy of free space	$\varepsilon_{fs} = 10$ pJ/bit/m^2
Amplifier energy of multi-path	$\varepsilon_{mp} = 0.0013$ pJ/bit/m^4

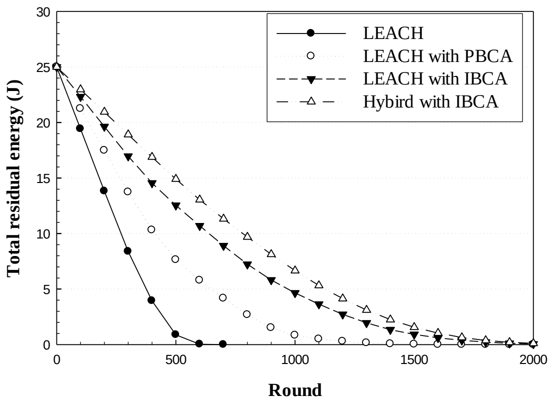

Fig. 6. Comparison of total residual energy each round

The number of deceased nodes each round for four architectures are shown in Fig. 7. In the original LEACH architecture, the first node dies at about round 290, and the 20th node dies at about round 354. In the LEACH architecture with PBCA, the first node dies at about round 301, and the 20th node dies at about round 397, while in LEACH architecture with IBCA, nodes die at rounds 315 and 409, respectively. However, the first node perishes at about round 372, and the 20th at round 537 in the hybrid architecture with IBCA. Therefore, it is demonstrated that our hybrid architecture with

IBCA has the lowest sensor node mortality rate, while the original LEACH architecture has the highest.

Total sensing area is shown in Fig. 8. Prior to round 300, the four architectures cover the same sensing area. After round 500, the hybrid architecture with IBCA maintains the largest sensing area, and the original LEACH the smallest. Thus, it is shown that for sensing area each round, the hybrid architecture with IBCA covers the maximum sensing area, while the original LEACH covers the minimum. The main reason for this is that the hybrid architecture with IBCA has an extended system lifetime.

In addition, we changed the sensing radius to, and compared the performances of the three WSN architectures in Figs. 9-11.

As shown in Fig. 9, the total residual energy of the original LEACH was depleted at round 700. The residual energy of LEACH with PBCA was 6.6 J at round 700, and the residual energy of LEACH with IBCA was 11 J at round 700. However, the residual energy of the hybrid architecture with IBCA was 13 J at round 700. Our novel scheme, the hybrid architecture with IBCA, and LEACH with IBCA obtain greater total residual energy than the other architectures.

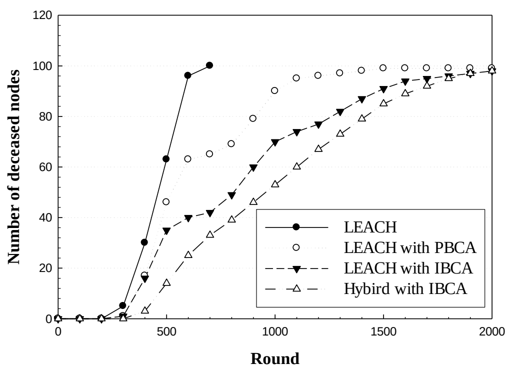

Fig. 7. Comparison of the number of deceased nodes each round

As can be seen in Fig. 10, the first node dies at about round 292, and the 20th node dies at about round 365 in the original LEACH architecture. In the LEACH with PBCA architecture, the first node dies at about round 311, and the 20th node dies at about round 406. In the LEACH with IBCA architecture, this does not occur until approximately rounds 320, and 418, respectively. However, in our novel scheme, the hybrid architecture with IBCA, the first node dies at about round 370, and the 20th at round 587. Therefore, it is demonstrated that our hybrid architecture with IBCA extends node lifespan more than other architectures do.

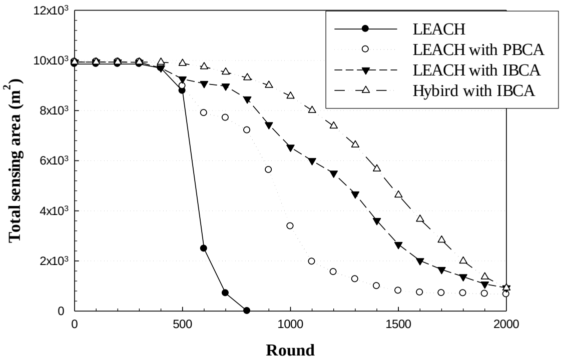

Fig. 8. Comparison of total sensing area each round.

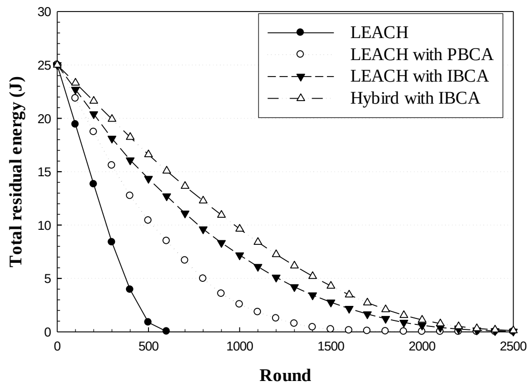

Fig. 9. Total residual energy for $R_s = 18$ m

As demonstrated in Fig. 11, subsequent to round 580, our hybrid architecture with IBCA maintains the largest sensing area, while the original LEACH maintains the smallest. Prior to round 410, the hybrid architecture with IBCA covers the same sensing area as do LEACH with PBCA and LEACH with IBCA, which is larger than that covered by the LEACH architecture alone.

Furthermore, we assume that each node has a sensing radius of $R_s = 15$ m , and number of bits $l = 6000$ bits . We compare the WSN performance of the three architectures in Figs. 12-14.

As shown in Fig. 12, the original LEACH runs out of energy at round 500, the LEACH with PBCA has 3.4 J at round 500, and the LEACH with IBCA has 8.1 J at round 500. The hybrid architecture with IBCA has 10.5 J at round 500. Our novel scheme, the hybrid architecture with IBCA, obtains the maximum total residual energy.

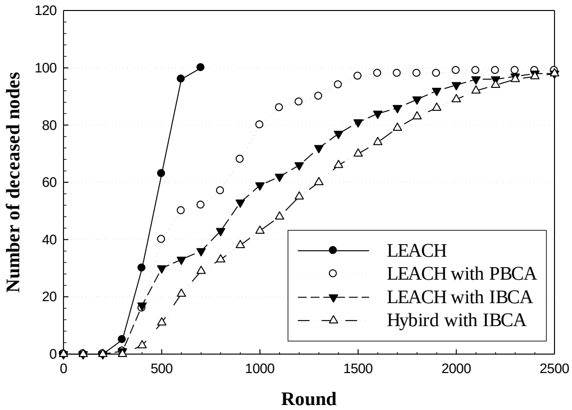

Fig. 10. Number of deceased nodes for $R_s = 18$ m

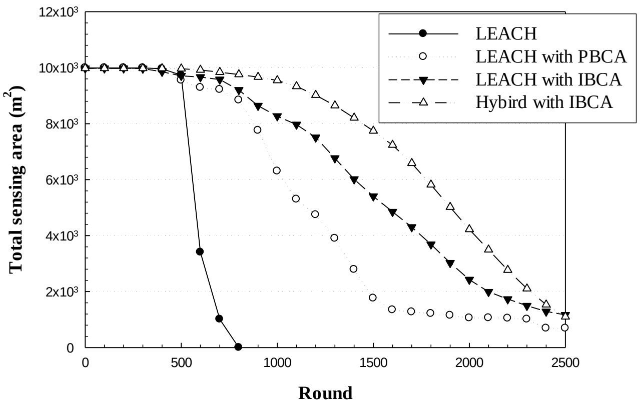

Fig. 11. Total sensing area for $R_s = 18$ m

As can be seen from Fig. 13, the first node dies at about round 188, and the 20th node dies at about round 218 for the original LEACH, while in the LEACH with PBCA, the first and 20th nodes die at about rounds 200, 254, respectively. In the LEACH with IBCA architecture, nodes die at about rounds 203, 277, respectively. However, in the hybrid architecture with IBCA, the first node dies at about round 226, and the 20th at about round 371. It is demonstrated that the hybrid architecture with IBCA has extended the nodes' lifetime more than the original LEACH, the LEACH with PBCA, and the LEACH architecture with IBCA have.

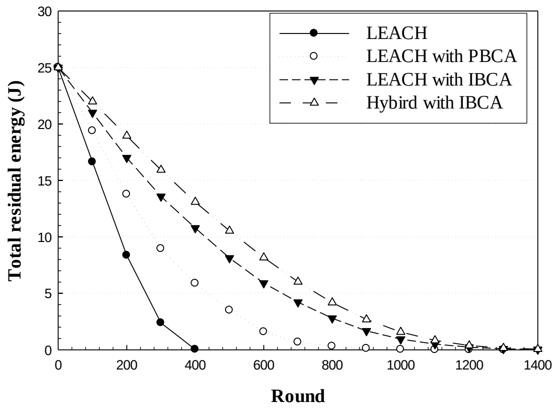

Fig. 12. Total residual energy for $R_s = 15$ m and $l = 6000$ bits .

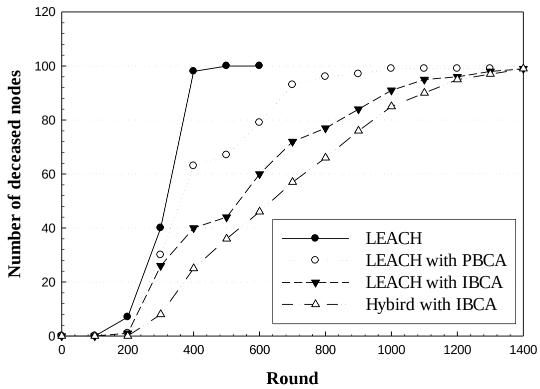

Fig. 13. Number of deceased nodes for $R_s = 15$ m and $l = 6000$ bits .

Fig. 14 shows that the hybrid architecture with IBCA maintains the largest sensing area subsequent to round 320, while the original LEACH architecture maintains the smallest.

As shown in Figs. 6-14, we ran simulations for different packets and different node sensing ranges. Notwithstanding these different input parameters, we obtained the same results for every simulation. Therefore, our proposed algorithms consistently outperform the original LEACH architecture and the LEACH architecture with PBCA, in terms of energy consumption, number of live nodes and sensing area.

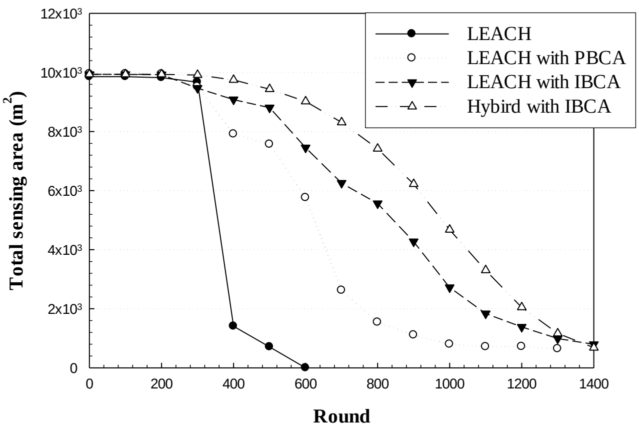

Fig. 14. Total sensing area for $R_s = 15$ m and $l = 6000$ bits

6. Conclusions

In this paper, we proposed a novel hybrid architecture with IBCA, and LEACH architecture with IBCA. Our novel hybrid architecture is based on both PEGASIS and LEACH architecture, with the four features that (a) it requires that only one leader perform data aggregation and transmit data to the BS for each round, (b) each sensor node must serve as the leader once each round, (c) the minimum transmission distance between nodes is guaranteed, and (d) it requires less aggregated data packets than does PEGASIS. In the hybrid architecture, the data aggregation task is assigned to a plurality of nodes, decreasing the energy required during the data transmission. Our proposed architectures use IBCA that the WSN's sensor nodes are classified into two types, i.e., active nodes, which responsible for detecting data, and the sleep mode nodes, which remain idle. Therefore, the entire system requires less live sensor nodes to cover a sensor field. The nodes to enter sleep mode are determined using IBCA, and do not perform any functions, which reduces energy consumption. Finally, the system is constructed using only active nodes, further reducing the energy consumption of the WSN. On the other hand, IBCA selected a greater number of redundant nodes than did PBCA, the main reason being that, with IBCA, a greater number of sensor nodes can be used for judgment. For this reason, the application of IBCA to the hybrid architecture improves the system lifetime.

Simulation results show that our proposed hybrid architecture with IBCA, and IBCA combined with LEACH demonstrate excellent performance compared with both the original LEACH architecture and LEACH architecture combined with PBCA, in terms of total residual energy, death rate of sensor nodes and total sensing area.

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References

1. Al-Karaki, J. N., Ul-Mustafa, R., Kamal, A. E.: Data Aggregation and Routing in Wireless Sensor Networks: Optimal and Heuristic Algorithms. Computer Networks, Vol. 53, No. 7, 945-960. (2009)
2. Burrell, J., Brooke, T., Beckwith, R.: Vineyard Computing: Sensor Networks in Agricultural Production. IEEE Pervasive Computing, Vol. 3, No. 1, 38-45. (2004)
3. Estrin, D., Girod, L., Pottie, G., Srivastava, M.: Instrumenting the World with Wireless Sensor Networks. In Proceedings of the IEEE International Conference on Acoustics, Speech, and Signal Processing. Salt Lake City, USA, 2033-2036. (2001)
4. Akyildiz, I. F., Su, W., Sankarasubramaniam, Y., Cayirci, E.: A Survey on Sensor Networks. IEEE Communications Magazine, Vol. 40, No. 8, 102-114. (2002)
5. Kumarawadu, P., Dechene, D. J., Luccini, M., Sauer, A.: Algorithms for Node Clustering in Wireless Sensor Networks: A Survey. In Proceedings of the IEEE 4th International Conference on Information and Automation for Sustainability. Colombo, Sri Lanka, 295-300. (2008)
6. Bonnet, P., Gehrke, J., Seshadri, P.: Querying the Physical World. IEEE Personal Communications, Vol. 7, No. 5, 10-15. (2000)
7. Islam, M. J., Islam, M. M., Islam, M. N.: A-sLEACH: An Advanced Solar Aware LEACH Protocol for Energy Efficient Routing in Wireless Sensor Networks. In Proceedings of the IEEE 6th International Conference on Networking. Sainte-Luce, France, 1-4. (2007)
8. Jin, Y., Liu, R., He, X., Huang, Y.: A distributed power management design based on MOST networks. Computer Science and Information Systems, Vol. 8, No. 4, 1097-1115. (2011)
9. Qian1, Q., Shen, X., Chen, H.: An Improved Node Localization Algorithm Based on DV-Hop for Wireless Sensor Networks. Computer Science and Information Systems, Vol. 8, No. 4, 953-972. (2011)
10. Heinzelman, W. B., Chandrakasan, A. P., Balakrishnan, H.: An Application-Specific Protocol Architecture for Wireless Microsensor Metworks. IEEE Transactions on Wireless Communications, Vol. 1, No. 4, 660-670. (2002)
11. Yigitel, M. A., Incel, O. D., Ersoy, C.: Design and Implementation of A QoS-Aware MAC Protocol for Wireless Multimedia Sensor Networks. Computer Communications, Vol. 34, No. 16, 1991-2001. (2011)
12. Guo, P., Jiang, T., Zhang, K.: Novel 2-Hop Coloring Algorithm for Time-Slot Assignment of Newly Deployed Sensor Nodes without ID in Wireless Sensor and Robot Networks. Computer Communications, Vol. 35, No. 9, 1125-1131. (2012)
13. Karkvandi, H. R., Pecht, E., Yadid-Pecht, O.: Effective Lifetime-Aware Routing in Wireless Sensor Networks. IEEE Sensors Journal, Vol. 11, No. 12, 3359-3367. (2011)
14. Huang, B., Hao, F., Zhu, H., Tanabe, Y., Baba, T.: Low-Energy Static Clustering Scheme for Wireless Sensor Network. In Proceedings of the IEEE International Conference on Wireless Communications, Networking and Mobile Computing. Wuhan, China, 1-4. (2006)
15. Wei, B., Hu, H. Y., Fu, W.: An Improved LEACH Protocol for Data Gathering and Aggregation in Wireless Sensor Networks. In Proceedings of the IEEE International Conference on Computer and Electrical Engineering. Phuket, Thailand, 398-401. (2008)
16. Lindsey, S., Raghavendra, C. S.: PEGASIS: Power-Efficient Gathering in Sensor Information Systems. In Proceedings of the IEEE Aerospace Conference. Big Sky, Montana, 1125-1130. (2002)
17. Lindsey, S., Raghavendra, C., Sivalingam, K. M.: Data Gathering Algorithms in Sensor Networks Using Energy Metrics. IEEE Transactions on Parallel and Distributed Systems, Vol. 13, No. 9, 924-935. (2002)
18. Chen, Y. L., Lin, J. S.: Energy Efficiency Analysis of a Chain-Based Scheme via Intra-Grid for Wireless Sensor Networks. Computer Communications, Vol. 35, No. 4, 507-516. (2012)

19. Huang, C. F., Tseng, Y. C.: The Coverage Problem in a Wireless Sensor Network. In Proceedings of the ACM 2nd International Conference on Wireless Sensor Networks and Applications. San Diego, USA, 115-121. (2003)
20. Quang, V. T., Takumi, M.: An Algorithm for Sensing Coverage Problem in Wireless Sensor Networks. In Proceedings of the IEEE Sarnoff Symposium. Princeton, New Jersey, 1-5. (2008)
21. Quang, V. T., Takumi, M.: A Novel Gossip-Based Sensing Coverage Algorithm for Dense Wireless Sensor Networks. Computer Networks, Vol. 53, No. 13, 2275-2287. (2009)
22. Wang, X., Xing, G., Zhang, Y., Lu, C., Pless, R., Gill, C.: Integrated Coverage and Connectivity Configuration in Wireless Sensor Networks. In Proceedings of the 1st International Conference on Embedded Networked Sensor Systems. Los Angeles, USA, 28-39. (2003)
23. Wang, X., Xing, G., Zhang, Y., Lu, C., Pless, R., Gill, C.: Integrated Coverage and Connectivity Configuration for Energy Conservation in Sensor Networks. ACM Transactions on Sensor Networks, Vol. 1, No. 1, 36-72. (2005)
24. Chen, Y. L., Cheung, F. K., Chang, Y. C.: A Low-Energy Adaptive Clustering Hierarchy Architecture with an Intersection-Based Coverage Algorithm in Wireless Sensor Networks. In Proceedings of the Seventh International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing, Taichung, Taiwan. (2013)
25. Chen, Y. L., Wang, N. C., Shih, Y. N., Lin, J. S.: Improving Low-Energy Adaptive Clustering Hierarchy Architectures with Sleep Mode for Wireless Sensor Networks. Wireless Personal Communications, Vol. 75, No. 1, 349-368. (2014)

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