RICA: a ring-based information collection architecture in wireless sensor networks

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Abstract: We propose a novel data collection architecture, called Ring-based Information Collection Architecture (RICA), for sensor networks. In the RICA scheme, sensors are organised into a ring. According to our study, the transmission delay time of data collection in a ring is only a half of that in PEGASIS, in which sensors are organised into a chain. We present a ring construction algorithm for RICA, which can reduce the average transmission distance between every pair of adjacent sensors. In addition, we also propose another scheme, called L-RICA, to further reduce the transmission delay time of RICA. L-RICA makes use of a layered-ring architecture for concurrent transmissions. Simulation results show that RICA indeed has longer-life time and lower $Energy \times Delay$ than both the cluster-based scheme (e.g. LEACH) and the chain-based scheme (e.g. PEGASIS). Compared to other layered architecture, L-RICA outperforms the chain-based binary and chain-based three-level schemes.

Keywords: wireless sensor networks; data gathering protocols; ring-based architecture; energy-efficient operation.

Reference to this paper should be made as follows: Huang, S-C., Jan, R-H. and Yang, W. (2006) 'RICA: a ring-based information collection architecture in wireless sensor networks', *Int. J. Sensor Networks*, Vol. 1, Nos. 3/4, pp.190–199.

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1 Introduction

A sensor network consists of a large number of low-cost, low-power sensor nodes (Warneke and Pister, 2002). These tiny micro-devices are deployed in specific environments for collecting information. For example, they are used for military surveillance, forest fire detection and outer space exploration (Akyildiz et al., 2002; Chong and Kumar, 2003; Rajaravivarma et al., 2003). Generally, the energy of a sensor node comes from its equipped battery. Because the scale of a sensor network is usually very large and the deployed environments are usually dangerous or hostile, recharging the equipped battery of sensor nodes is deemed impossible or infeasible. Therefore, conserving battery energy is critical for extended operations. Developing an energy-efficient scheme becomes a main research topic in the study of sensor networks.

The simplest way to collect data was for each sensor node to transmit its data to the base station directly. This is called the *direct* scheme. In the direct scheme, data may be transmitted over a long distance to reach the base station. Therefore, the direct scheme will drain the battery energy of sensors quickly. Several cluster-based schemes (Boukerche et al., 2003; Heinzelman et al., 2000; Liu and Lin, 2003; Manjeshwar and Agrawal, 2001; Younis et al., 2002) were proposed in an attempt to reduce the average transmission distance so that the sensors' battery could last longer.

Generally, in cluster-based schemes, the sensor nodes are divided into several *clusters*. Each cluster designates a *Cluster Head* (CH) to serve as the local base station of the cluster. Other sensor nodes in the same cluster will forward their data to the CH directly. Then the CH forwards the aggregated data to the base station. After the aggregated data has been forwarded, a new CH will be elected from the living sensors. Sensors take turns to serve as CH in order to balance the energy consumption of all sensors. Hopefully, the whole sensor network can operate for a longer period of time. $LEACH$ (Heinzelman et al., 2000) adopts such a cluster-based scheme. Some tree-based schemes (Lu et al., 2004; Thepvilojanapong et al., 2005) are also variations of cluster-based schemes.

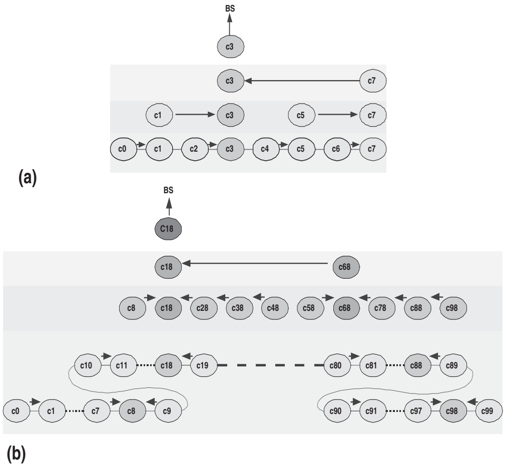
Although cluster-based schemes do improve the energy efficiency, all the CHs still need to transmit data to the base station directly. Energy can be further conserved if only one node (which will be called the *leader*) has to transmit data directly to the base station. On the basis of this consideration, chain-based schemes, such as PEGASIS (Lindsey and Raghavendra, 2002), are proposed in which sensors are organised into a chain and one node serves as the leader. In chain-based schemes (Du et al., 2003; Lindsey and Raghavendra, 2002; Lindsey et al., 2002), each sensor has one or two neighbours. Each sensor node combines one neighbour's data and its own data and then forwards the combined data to the other neighbour. Eventually, all data will reach the leader, which will then forward the aggregated data to the base station. In PEGASIS, all nodes take turns to serve as the leader. The transmission distances of non-leader nodes are reduced. Therefore, chain-based systems are more energy-efficient than cluster-based systems.

On the other hand, the transmission delay time in a chain-based system would be longer than that in a cluster-based system. The worst scenario occurs when data is collected by the node at one end of the chain while the leader is at the other end. In this case, data needs to pass through $N - 1$ hops to reach the leader, where N is the total number of sensors in the chain. To remedy this flaw, the chain-based binary scheme and the chain-based three-level scheme were proposed (Lindsey et al., 2002).

In a chain-based binary scheme, shown in Figure 1(a), N sensors are divided into $N/2$ pairs. Each pair consists of two adjacent nodes in the chain. One of them is designated as the *primary node* of the pair. Then the $N/2$ primary nodes are linked into a higher-level chain. The higher-level chain is similarly divided into pairs of adjacent nodes and the primary nodes are linked into yet another chain (containing $N/4$ nodes). This organisation repeats itself until only a single node remains, which serves as the *leader*. The leader is responsible for transmitting the aggregated data to the base station. The maximum number of relays in a chain-based binary scheme is $\lceil \log_2 N \rceil + 1$ hops (where 1 accounts for forwarding data from the leader to the base station).

The chain-based three-level scheme, shown in Figure 1(b), is similar to the binary scheme but it limits the hierarchy to three levels. Thus, each level will contain multiple sub-chains. In both schemes, all nodes take turns to play the role of the leader. Note that the chain-based three-level approach has reduced the transmission time of PEGASIS at a little extra overhead. It is possible to further reduce transmission delay time if the leader is always in the middle node in each chain.

Figure 1 (a) The chain-based binary scheme and (b) the chain-based three-level scheme



In this paper, we purpose a novel data gathering scheme, called the *Ring-based Information Collection Architecture* ($RICA$), which aims at reducing the transmission delay time. In RICA, the sensors are organised into a minimum-distance ring. The distance (i.e. cost) of a ring is defined as the sum of the geographic distance between every pair of adjacent sensors in the ring. Constructing a ring of the minimum distance is similar to solving the travelling-salesman problem, which is a known NP-complete problem. Thus, we use a heuristic algorithm, called the TriAngle Ring COnstruction algorithm (TARCO), to construct a low-distance ring. This algorithm also improves the energy efficiency of RICA.

We also propose yet another scheme, called Layered RICA (*L-RICA*), which makes use of a layered architecture and concurrent transmissions to reduce the transmission delay time. Simulation results show that the transmission delay time of RICA is only a half of that in PEGASIS. L-RICA also outperforms the chain-based binary and three-level schemes as well as the cluster-based schemes. Furthermore, simulation results also show that TARCO constructs rings that is more energy-efficient for RICA.

The rest of this paper is organised as follows. In Section 2, we introduce our radio energy model. RICA and TARCO are discussed in Sections 3 and 4, respectively. L-RICA is introduced in Section 5. In Section 6, we present the simulation results to evaluate each scheme. Finally, we give the conclusion in Section 7.

2 Radio energy model

In this paper, we use the same radio energy model as in (Heinzelman et al., 2000). In this model, a sensor is able to control and adjust its transmission power. Thus, it can use the minimum necessary energy when sending data to the intended recipients. The energy that is required for switching the transmitter (or receiver) circuits on for dissipating one bit of data is denoted as $E_{\text{elec}} = 50$ nJ/bit. The energy needed by a transmitter amplifier for dissipating one bit of data is denoted as $\epsilon_{\text{amp}} = 100$ pJ/bit/m^2. The radio loss in this model is proportional to the square of the distance (under the assumption of a free-space environment). Thus, the energy for sending data includes that for the transmitter circuits and that for the transmitter amplifier. The energy for receiving data includes only that for the receiver circuits. In the following equations, $E_{tx}(k, d)$ is the energy for a sensor to transmit a k-bit message and $E_{rx}(k)$ is the energy to receive a k-bit message, where d is the distance for transmitting data.

$$E_{tx}(k, d) = E_{tx-\text{elec}}(k) + E_{tx-\text{amp}}(k, d) \quad (1)$$

$$E_{rx}(k) = E_{rx-\text{elec}}(k) \quad (2)$$

Transmission energy includes that for the transmitter circuits (Equation (3)) and for the signal amplifier (Equation (4)).

$$E_{tx-\text{elec}}(k) = E_{\text{elec}} \times k \quad (3)$$

$$E_{tx-\text{amp}}(k, d) = \epsilon_{\text{amp}} \times k \times d^2 \quad (4)$$

Reception energy includes only that for the receiving circuits (Equation (5)).

$$E_{rx}(k) = E_{\text{elec}} \times k \quad (5)$$

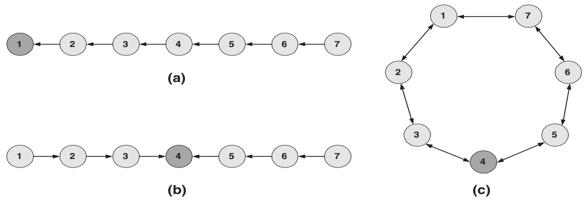
Under this model, reducing the transmission distance and the data size can conserve the battery energy of a sensor. A sensor can shrink the data size by aggregating data from several sensors (Petrovic et al., 2003). Schemes such as LEACH and PEGASIS are proposed for reducing the average transmission distance. The RICA scheme proposed in this paper also attempts to reduce the average transmission distance.

3 Ring-based information collecting architecture

In a chain-based scheme, such as PEGASIS, the worst transmission time (which is defined as the number of hops a message travels) will affect the choice of the leader. For example, as Figure 2(a) shows, if sensor 1 is the leader, the worst transmission time is seven hops because node 7 has to pass its data through node 6 to node 1 then to the base station. On the other hand, if node 4 is the leader, as shown in Figure 2(b), the worst transmission time is four hops, from both node 7 and node 1 to the base station. Therefore, in a chain-based scheme, if the leader is always the middle node, the transmission time will be the least.

However, if the middle node always serves as the leader, its energy will quickly exhaust. This will bring down the whole sensor network. Thus, if the sensor nodes are organised into a ring topology, as shown in Figure 2(c), every node is the middle node of some chain. Hence, all nodes can take turns to serve as the leader while energy consumption is roughly balanced. The whole sensor network can last longer. This motivates our RICA scheme.

Figure 2 The linear chain of PEGASIS

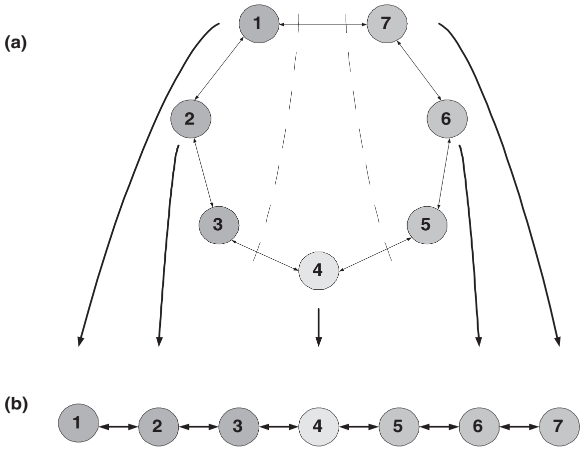


RICA arranges sensor nodes into a ring topology. There are several methods to build a ring of sensors. The simplest method is to link the first and the last nodes of the chain in a chain-based scheme, such as PEGASIS.

The sensor nodes are assigned identities 1 through N, where N is the total number of nodes. At the beginning of this protocol, the base station can broadcast a message to each sensor, informing each its identity. Every node knows its left and right neighbors based on the identities. The nodes take turns to serve as the leader. Within a circle of message transmission, all nodes except the leader are divided into two equal-sized groups. Nodes in the left group transmit their data to their respective right neighbours. Similarly for nodes of the right group.

For example, in Figure 3(a), all nodes are linked into a ring topology. Assume node 4 is the current leader. This ring is stretched into a chain, as shown in Figure 3(b). Both the left and the right groups consist of three nodes. Nodes 1, 2 and 3, which are located in the left group, forward their data to their respective right neighbours. Similarly for nodes 4, 5 and 6.

Figure 3 Stretch a ring into a linear chain



In RICA, the sensors are assigned identities $1, 2, \ldots, N$, respectively. A leader is selected according to the identities. Node 1 is the leader in the first round, node 2 is the leader in the second round, etc. Once a leader has been selected, every node can decide the group it belongs to and the direction of data transmission. Figure 4 shows the algorithm for each sensor to determine its group and the direction of data transmission.

Suppose the current message transmission is the mth round and the leader's identity is L_m. Every node X uses L_m and its own identity, ID_X, to determinate its group. For example, in a 10-node network, assume $L_m = 9$. The node X with identity 5 will calculate $(5 + 10 - 9 + 5) \bmod 10 = 1 < (10/2)$ and determines it is in the right group.

Figure 4 Algorithm for a node to decide its group

```
$L_m$ : identity of the leader in the mth round
$ID_X$ : identity of node X
$ID_{next}$ : identity of the forwarding neighbour node
procedure Group_Det ($L_m$)
begin
  $half := \lfloor \frac{N}{2} \rfloor$
  $k := (ID_X + (N - L_m) + half) \bmod N$          (*)
  if $k \geq half$ then   /* $X \in$ the left group */
      $ID_{next} := ((ID_X - 1)) \bmod N$
  else   /* $X \in$ the right group */
      $ID_{next} := ((ID_X + 1) + N) \bmod N$
  end if
end
```

When an intermediate node fails (such as running out of energy), it can passively or actively indicate the failure to the base station and its neighbours. In passive indication, the failed node's predecessor will not be able to receive the acknowledge frame. Thus, its predecessor will embed the identity of the failed node in the retransmission message and re-send it to the successor of the failed node directly. In active indication, each sensor in the network monitors its own remaining power. While a node realises its remaining power is less than a threshold (for example, the remaining energy can sustain only one more round), it will embed its identity in the forwarding message to inform the base station that it will leave the network in the next round. Its predecessor has also been informed its status in the acknowledge frame so that the predecessor will bypass the failing node and send the data to its successor directly in the next round. Because active indication can reduce the energy consumed in re-transmission, it is better than passive indication.

4 Triangle ring constructing algorithm

The chain in PEGASIS is created by a closest-neighbour algorithm, which is a greedy algorithm. The closest-neighbour algorithm first selects the node that is farthest away from the base station as the leader. Initially, the chain consists solely of the leader. Then the node that is closest to the leader is added into the chain. Then the node that is closest the one just added is added to the chain. Successive neighbours are selected in this manner from the remaining nodes until all nodes are added to the chain.

An alternative algorithm for chain creation that attempts to reduce the total length of the chain was proposed by Du et al. (2003). In the beginning, the chain consists of the node that is farthest away from the base station. The second node is also the closest neighbour to the farthest node. After that, the node that is not already in the chain and that induces the least additional length to the current chain is added. Newly added node will be inserted into the chain. If its insertion position is already at one end of the current chain, the new node will be simply appended to the chain; otherwise, it will be inserted between two adjacent nodes of the current chain.

In the previous section, RICA creates a ring by linking the first and the last nodes of a chain constructed in PEGASIS. It is obvious that RICA will be more energy-efficient if Du et al.'s algorithm is used. However, Du et al.'s algorithm is not effective in reducing the total transmission distance. The reason is that the first sensor and the last sensor may be very far away from each other and, hence, their communication consumes a lot of energy in each round. Therefore, we propose a new algorithm, named TARCO, to create a ring for use in RICA. TARCO aims at reducing the average transmission distance between a pair of adjacent sensors.

Figure 5 shows the TARCO algorithm. To create a ring, TARCO consists of two phases – the link phase and the fix phase. At the link phase, the three nodes that are closest to the base station form the initial ring. Other nodes are added to the ring one by one. In each step, the node that, when added to the existing ring, induces the least total distance is added to the existing ring. The newly added node is inserted between two adjacent nodes.

At the end of the link phase, all nodes are linked in a ring.

Figure 5 Algorithm for deciding the group a node belongs to

```
$BS$ : base station
$RING$ : set of nodes already added to the ring
$N$ : set of all nodes
$N'$: set of nodes not in the ring yet
$Dist(a, b)$ : distance from node $a$ to node $b$
$ID(a)$ : the identity of node $a$
$Pos(a)$ : position of node $a$ in the ring
/* Link Phase */
$RING := \{C_0, C_1, C_2\}$;
/* $C_0, C_1, C_2$ are the 3 nodes closest to the BS */
$N' := N - RING$;
$D_{sum} := Dist(C_0, C_1) + Dist(C_1, C_2) + Dist(C_2, C_0)$;
while ( $N' \neq \emptyset$ ) do
  /* find the node with minimum $D_{sum}$ */
  $D_{min} := \infty$;
  for $C_j \in RING$ do
    for $C_i \in N'$ do
      $D_{new} := D_{sum} + Dist(C_j, C_i) +$
            $Dist(C_i, C_{j+1}) - Dist(C_j, C_{j+1})$;
      if $D_{new} < D_{min}$ then
        $D_{min} := D_{new}$; $N_{min} := i$; $index := j$;
      end if
    end for
  end for
  $N_{min} := i$;
  insert $N_{min}$ to $RING$, within $C_{index}$ and $C_{index+1}$;
  $N' := N' - \{N_{min}\}$;
  $RING := RING \cup \{N_{min}\}$;
end while
/* Fix Phase */
$ringCost$ := total length of the $RING$;
for $C_i \in RING$ do
  for $C_j \in RING$ do
    if $Pos(C_j) \neq Pos(C_i) + 2$ then continue;
    else
      $Leng_1 := Dist(C_i, C_{i+1}) + Dist(C_j, C_{j+1})$;
      $Leng_2 := Dist(C_i, C_j) + Dist(C_{i+1}, C_{j+1})$;
      if $ringCost - Leng_1 + Leng_2 > ringCost$ then
        reverse the order of RING from $C_{i+1}$ to $C_j$;
      end if
    end if
  end for
end for

Re-assign all sensors' IDs in counter-clockwise.
```

Let `ringCost` denote the total distance of the ring. A closer examination of a ring may discover that two edges may cross each other, as shown in Figure 6(a).

It is possible to reduce the total length of a ring if the two crossing edges are replaced by two non-crossing edges, as shown in Figure 6(b). During the fix phase, crossing edges, such as $(i, i+1)$ and $(j, j+1)$, are replaced by non-crossing edges, such as (i, j) and $(i+1, j+1)$, if the total length of the ring could be reduced. The edge-replacement operations will maintain a ring topology but the total ring length is reduced. The ring obtained at the end of the fix phase will be used in RICA.

Figure 6 The case of crossing edge of ring

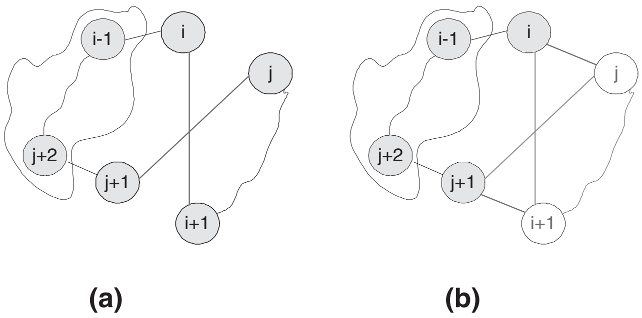


Figure 7 shows an example of TARCO's two phases. In Figure 7(a), nodes a, b and c form the initial ring. In the next step, node e, which, when added to the initial ring, induces the least total length, is added to the initial ring. The new ring is shown in Figure 7(b). Nodes j, f, e, k, i, h, d, g are similarly added to the ring one by one and in that order, which are shown in Figures 7(c)–(i). The resulting ring is shown in Figure 7(i). Note that `ringCost` $= 148$.

During the fix phase, the pair of crossing edges (g, f) and (b, e) is replaced by (g, e) and (b, f) because $148 - (21.5 + 14.1) + (12.9 + 12.7) = 138 < 148$. The final ring is shown in Figure 7(j).

The time complexity of TARCO is $O(n^3)$, which is the same as that of Du et al.'s chain-creating algorithm, where n is the number of sensors. But TARCO is performed only once, when the sensor network system starts up. Although using TARCO to construct a ring is a little more complex than PEGASIS, it can conserve energy and fairly share loading on data transmission.

5 Layered RICA scheme

In order to reduce the data propagation delay, we propose a layered data-collection algorithm, called L-RICA, which is a variation of RICA. L-RICA organises the sensors into layered rings. Firstly, we assume that all nodes are equipped with the CDMA communication ability (we will discuss later a modification for nodes without CDMA). Consider a ring of 100 sensors, in which every 5 contiguous sensors form a *section* (of the first layer), as shown in Figure 3. There are 20 sections. The middle node of each section is the *local leader* (i.e. leader for the section), who is responsible for collecting data from all members in the section. For example, in Figure 8, Section 1 consists of nodes $c1$, $c2$, $c3$, $c4$, and $c5$, in which $c3$ is the local leader. The local leaders of the first layer are organised into a ring (of the second layer). The second-layer ring is similarly divided into 5-node sections, in which the middle nodes are the local leaders. These local leaders similarly form a ring of an even higher layer, etc. For our 100-node sensor network, there will be three layers, as shown in Figure 8. In general, for an N-node sensor network, there will be $\lceil log_5 N \rceil$ layers.

If nodes lack the CDMA communication ability, we need to prevent interference from concurrent communication. Thus, the transmission mechanism in each section will be modified as in Figure 8(c). The right neighbour of the middle node, rather than the middle node itself, will serve as the leader so that the two ends of a section can communicate simultaneously without interference. Thus, the inter-section interference is also solved. In L-RICA, all nodes take turns to serve as the overall leader, who will send the aggregated data to the base station, in order to balance energy consumption. Sections are reorganised in each round by a counter-clockwise rotation.

For example, assume Figure 8(a) is the status of the layered ring in the 63rd round. Then Figure 8(b) is the status in the 64th round, in which node $c4$ is the local leader in Section 1 of the first layer (abbreviated L1S1), and nodes $c2$, $c3$, $c5$, and $c6$ are the members in L1S1.

To evaluate the transmission time of L-RICA with CDMA ability, we may count the number of hops for passing a sensor's data to the base station. We will use the 100-node network as an example. Because each section consists of five nodes, it takes at most 2 hops to transmit data from a non-leader to the corresponding local leader in the each layer. Finally, the overall leader needs to transmit the aggregated data to the base station. Thus, the total number of hops is at most $2 + 2 + 2 + 1 = 7$. In general, for an N-node network, the total transmission time in L-RICA is $\lceil log_5 N \times 2 + 1 \rceil$.

When the nodes are not equipped with the CDMA ability, the maximum number of hops in each section is 3. Thus, the total transmission time in a 100-node network is $3 + 3 + 2 + 1 = 9$.

6 Simulation

In order to obtain more realistic analysis, a *C* program is developed to simulate the operations of several schemes under various communication parameters.

6.1 Simulation set-up

For comparison with other schemes, we use the same parameters as in Lindsey et al. (2002). The network consists of 100 sensors, which are randomly deployed over two types of square areas: 50 m × 50 m and 100 m × 100 m. Each data packet is assumed to contain 2000 bits. Each sensor needs to aggregate its own data and data from neighbours. The energy consumption for aggregating data is assumed to be 5 nJ/bit. Energy consumption for transmitting and receiving circuits is assumed to be 50 nJ/bit and energy consumption for a transmitter amplifier to dissipate one bit of data is 100 $\mathrm{pJ/bit/m^2}$.

Figure 7 An example of TARCO

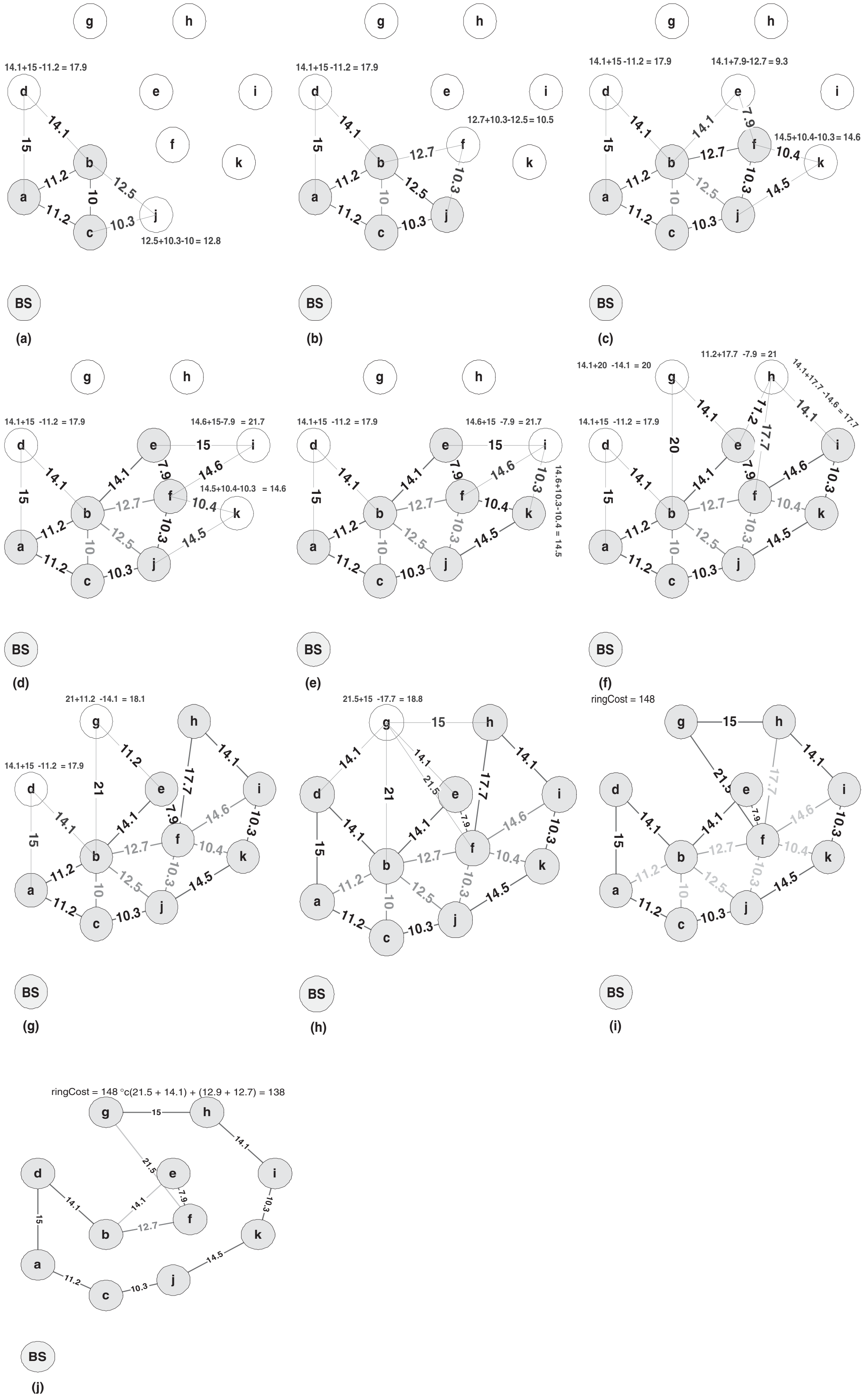
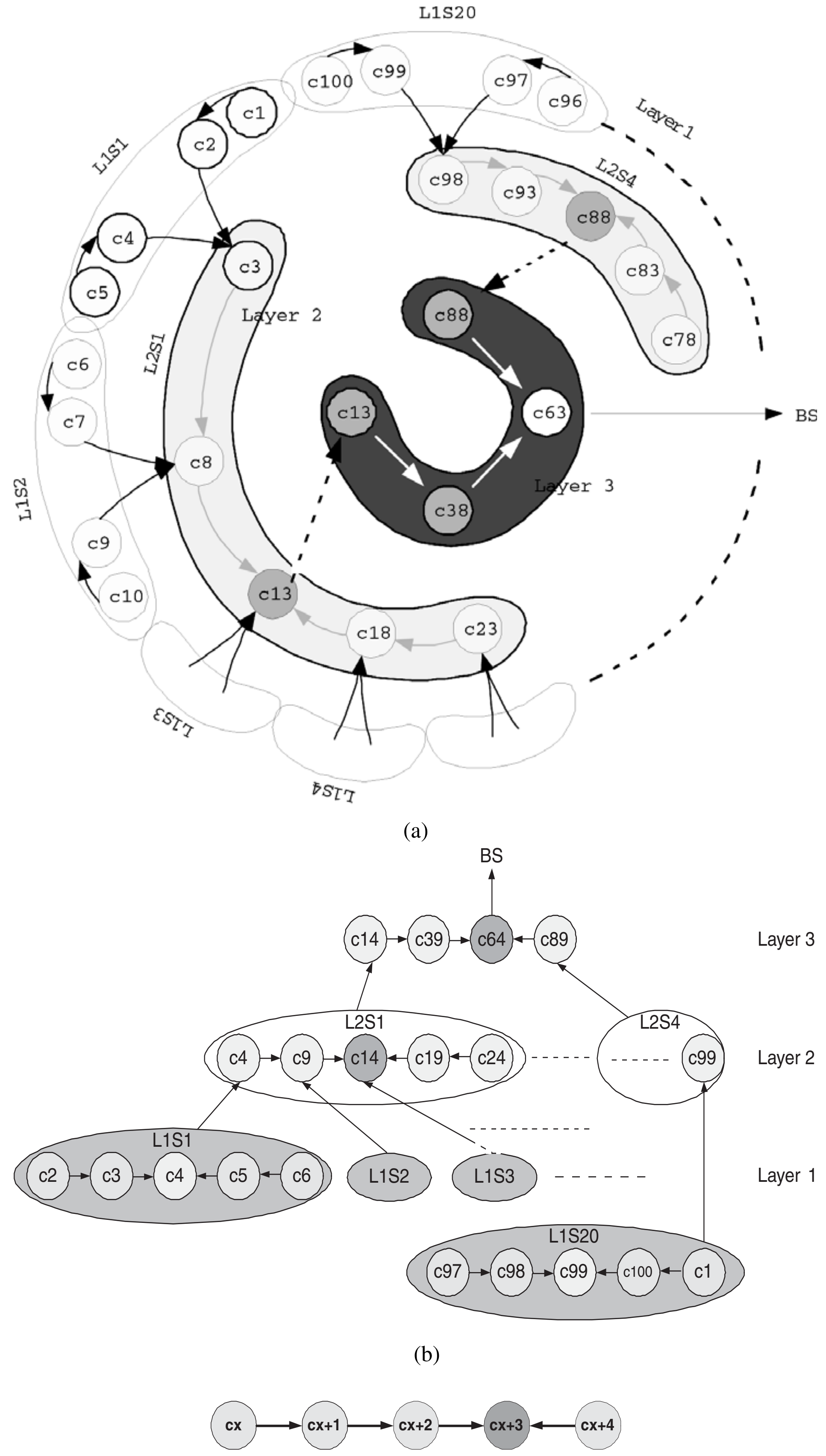


Figure 8 Example of the L-RICA scheme: (a) operation of L-RICA (round 63), (b) section leader selection (round 64) and (c) section transmissions of non-CDMA nodes



(a)

(b)

(c)

We measure the system operation time under the RICA, PEGASIS, LEACH and Direct schemes. In our simulation, system, operation time is expressed as the number of rounds of message transmission. A round is defined as all live sensors successfully transmitting their 2000-bit packets to the base station.

The second measurement is the *Energy* × *Delay* factor, as described in Lindsey et al. (2002). In evaluating a scheme, we need to consider both energy consumption and transmission delay time. In other words, a scheme with a small *Energy* × *Delay* factor is good at both saving energy and reducing packet delay time.

As in Lindsey et al. (2002), the interfering transmission's contribution in the CDMA system is assumed to be $1/128$ of the transmission energy. Without the CDMA ability, the interfering transmissions contribution is twice the amount of energy for a non-interference transmission.

6.2 Simulation results

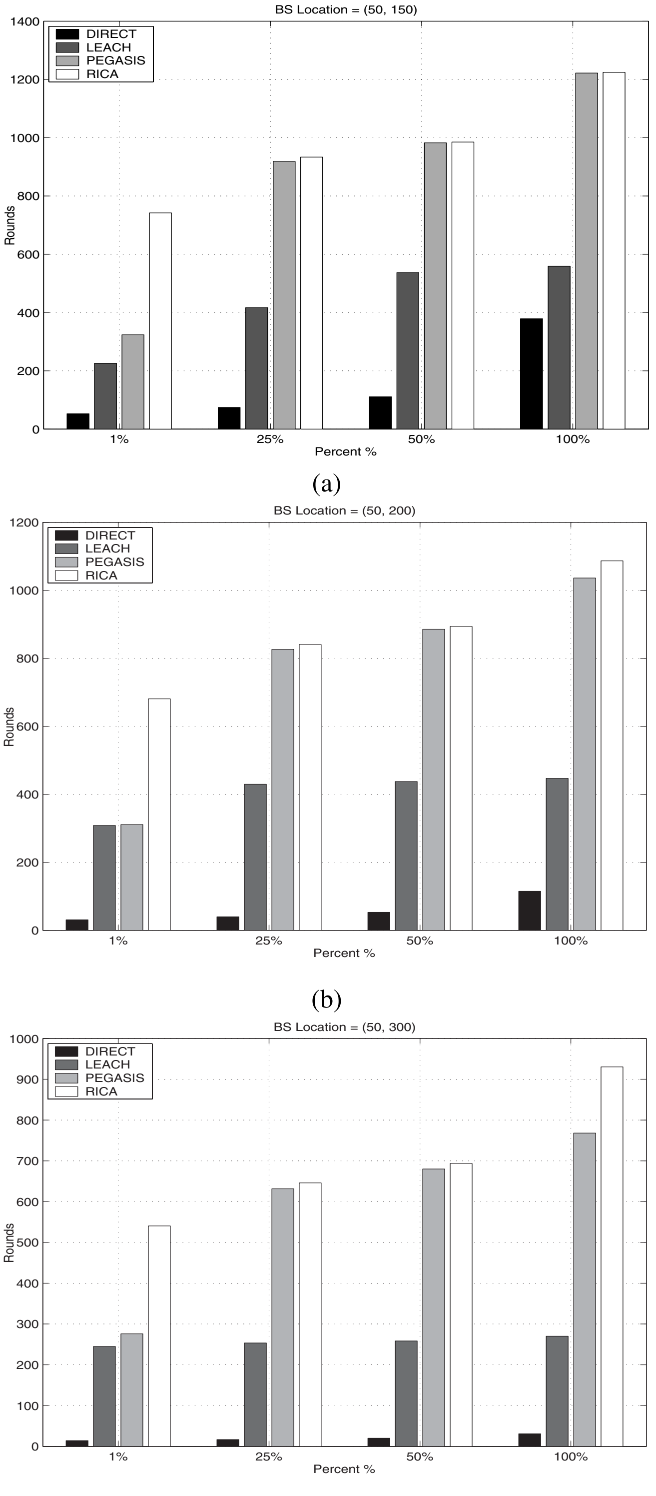
Figure 9 shows the number of rounds for the four schemes (DIRECT, LEACH, PEGASIS and RICA) before 1%, 25%, 50% and 100% of the nodes die, respectively. In this experiment, 100 sensors are randomly deployed over a 100 m × 100 m square area. Three base station locations – (50, 150), (50, 200), and (50, 300) – were tested. The results are shown in Figure 9(a)–(c).

From Figure 9(a), RICA can operate for more than 700 rounds before a first node dies while PEGASIS, LEACH and Direct operate for only 320, 220 and 50 rounds, respectively. The number of rounds before a first node dies under RICA is more than twice that under PEGASIS. This result shows that RICA can balance (and save) energy consumption among sensors more fairly than PEGASIS. In Figure 9(b) and (c), RICA shows its energy efficiency when the base station is located far away from the sensor network. The numbers of rounds before a first node dies in both Figures 9(b) and (c) are still twice that in PEGASIS.

Table 1 gives energy consumption, delay time and the $Energy \times Delay$ factor of a round under 8 schemes with 50 m × 50 m and 100 m × 100 m square areas, respectively. The base station is statically located at the positions (50, 150) and (50, 300) respectively (Note that the base station is located outside the square area).

Energy consumption is the average of 500 experiments. The delay time under each scheme is computed as the number of sequential transmissions, allowing as many concurrent transmissions as possible. Under the DIRECT scheme, sensors need to transmit data to the base station one at a time in order to avoid interference. Thus, the delay time is 100 since there are 100 sensors. The delay time under PEGASIS is also 100 because all nodes have to pass the aggregated data one by one. Under the LEACH, assume the number of cluster heads in the 100-sensor network is 5 and the number of nodes per cluster is 20. Hence, the delay time for each cluster is 19. After collecting data within the respective clusters, cluster heads transmit the aggregated data to the base station one by one. The delay time is 24 (i.e. $19 + 5$). Under the LEACH scheme, there are three additional steps, for electing a new cluster head in each round. Hence, the total delay time under LEACH is 27.

Figure 9 Rounds and dead node percentage under 100 × 100: (a) BS location (50, 150), (b) BS location (50, 200) and (c) BS location (50, 300)



(a)

(b)

(c)

The chain-based binary scheme makes use of a binary tree to transmit data. The maximum delay time is $\log_2 100 = 7$. An additional step is needed for the leader to transmit the aggregated data to the base station. Thus, the total delay time is 8. Under the chain-based third-level scheme, 10 nodes are grouped as a first-level subchain. Each subchain contains a local leader. The delay time in the first level is 9. In the second level, the ten leaders of the first level are divided

Table 1 Energy × Delay costs of different schemes (nodes $N = 100$)

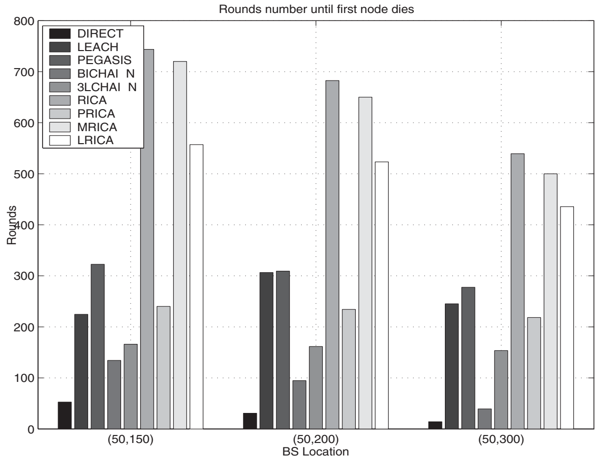
Scheme	*Energy*		*Delay*		*Energy × Delay*	
	50 × 50	*100 × 100*	*50 × 50*	*100 × 100*	*50 × 50*	*100 × 100*
DIRECT	0.32823	1.288469	$100(N)$		32.82315	128.8469
PEGASIS	0.02462	0.036494	$100(N)$		2.462516	3.649428
LEACH	0.08182	0.199908	$27(N/5 - 1 + 5N/100 + 3)$		32.82315	128.8469
Chain-based binary (cdma)	0.03291	0.053414	$8(log_2 N)$		0.263321	0.427309
Chain-based third-level (non-cdma)	0.03731	0.057071	$15(N/10 + N/20)$		0.559648	0.856066
RICA (TARCO)	0.02489	0.036036	$50(N/2)$		1.244691	1.801814
L-RICA (non-cdma)	0.03210	0.056031	$9(3 \times \lceil log_5 N \rceil + 1)$		0.2889	0.504279
L-RICA (cdma)	0.02652	0.041176	$7(2 \times \lceil log_5 N \rceil + 1)$		0.185682	0.288235

into two groups, each of which is a chain of five nodes. Thus, the delay time in the second level is 4. Finally, one of the two second-level leaders serves as the overall leader, which sends the aggregated data to the base station. Therefore, the total delay time under the chain-based third-level scheme is $9 + 4 + 2 = 15$. The delay time under RICA is a half of the total number of nodes, which is 50. The delay time of L-RICA is described in Section 5.

Table 1 gives that the $Energy \times Delay$ factor under RICA is a half of that under PEGASIS. L-RICA has better trade-off between energy consumption and delay time. The $Energy \times Delay$ factor under L-RICA (with CDMA) is the best among the eight examined schemes. Its value is only $2/3$ of that in a chain-based binary scheme and $1/3$ of that in a chain-based third-level scheme.

Figure 10 shows the number of rounds before a first node runs out of energy. P-RICA is a variation of RICA in which the ring is created by linking the first and the last nodes of the chain created in PEGASIS. M-RICA is a variation of RICA in which the ring is created by Du et al.'s algorithm (2003). The result shows that RICA (which uses TARCO to construct the ring) outperforms all the other schemes. P-RICA, however, cannot exhibit the benefits of a ring topology for balancing energy consumption. L-RICA achieves high energy balance at the cost of longer transmission time and more energy consumption.

Figure 10 The number of rounds before a first node dies



7 Conclusion

In this paper, we proposed RICA, a ring-based data collection architecture, for sensor networks. RICA organises the sensors into a ring topology. The transmission time under RICA is only a half of that in PEGASIS. To improve RICA, an accompanying ring construction algorithm, TARCO, is also proposed. TARCO creates a ring that shortens the average distances between two adjacent nodes. With the ring created by TARCO, RICA is even more energy-efficient in gathering data. Sensor networks under RICA last longer than those under other schemes. This means that RICA is good at balancing energy consumption.

In order to reduce data transmission delay, L-RICA was proposed. L-RICA makes use of a layered-ring architecture. Not only the transmission delay under L-RICA is shorter than that under all other examined schemes, but the energy consumption under L-RICA is also less than that under all other examined schemes. In addition, L-RICA also outperforms other schemes in terms of the $Energy \times Delay$ factor.

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