

Energy-aware node placement, topology control and MAC scheduling for wireless sensor networks

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ABSTRACT

In the WSNs, the nodes closer to the sink node have heavier traffic load for packet forwarding because they do not only collect data within their sensing range but also relay data for nodes further away. The unbalanced power consumption among sensor nodes may cause network partition. This paper proposes efficient node placement, topology control, and MAC scheduling protocols to prolong the sensor network lifetime, balance the power consumption of sensor nodes, and avoid collision. Firstly, a virtual tree topology is constructed based on Grid-based WSNs. Then two node-placement techniques, namely Distance-based and Density-based deployment schemes, are proposed to balance the power consumption of sensor nodes. Finally, a collision-free MAC scheduling protocol is proposed to prevent the packet transmissions from collision. In addition, extension of the proposed protocols are made from a Grid-based WSN to a randomly deployed WSN, enabling the developed energy-balanced schemes to be generally applied to randomly deployed WSNs. Simulation results reveal that the developed protocols can efficiently balance each sensor node's power consumption and prolong the network lifetime in both Grid-based and randomly deployed WSNs.

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1. Introduction

Wireless sensor networks (WSNs) have a wide range of potential applications including environment monitoring, military, smart house, and remote medical system [1–3]. A WSN comprises a sink node and an extremely large group of sensor nodes that communicate with each other in order to perform a broader sensing task. The sensor node is a tiny device with capabilities of sensing, data processing, and storing, and communication but has energy constraints. The sink node is an interface between the user and the WSNs through which the user can dispatch a query packet to sensor nodes. On receiving the query packet, the sensor nodes will transmit their sensing information according to the user's request.

In a WSN, sensors transmit the sensing information to the sink node in a multi-hop manner. As a result, sensor nodes closer to the sink node tend to exhaust their energy earlier due to the power consumption for packet forwarding. The unbalanced power consumption among sensor nodes may cause network partition, blocking the transmissions from sensor nodes to the sink node. Since the traffic load and power consumption of each node are location-dependent, the lifetime of a sensor network can be limited by the nodes with heavier traffic load. Therefore, power balance among sensors is an important issue and requires more effort to prolong the network lifetime [8].

Extensive research has focused on how to prolong the network lifetime. Different methods for reducing power consumption in WSNs have been explored in the available literature. Some research studies [4–6] proposed approaches to control each sensor's state in either active mode for packet forwarding or sleep mode for power saving. In [7,8], algorithms were proposed to help nodes make decision to sleep or join the backbone based on

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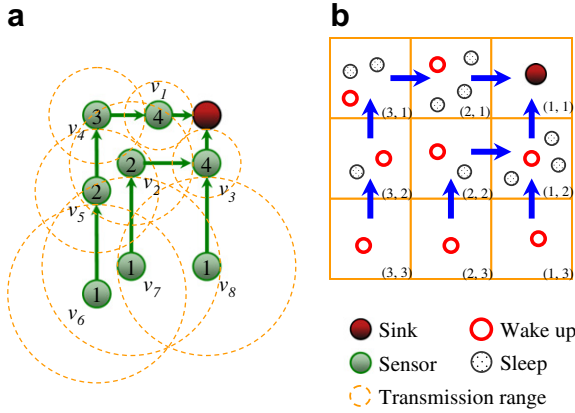


Fig. 2. (a) The Distance-based mechanism controls the distance of deployed sensors and uses power control to achieve energy-balance purpose. (b) The Density-based mechanism controls density of sensors in each zone. Sensors in each zone will stay in active mode in turn to achieve the energy-balanced goal.

zones. The basic idea of Density-based scheme is to adjust the density of sensor nodes in each zone. Since the sensor nodes in the zone closer to the sink node consume more energy for packet forwarding, the Density-based scheme deploys more sensor nodes in the zone closer to the sink node. In a zone, one of the sensor nodes stays in active mode in turn and the other sensor nodes stay in sleep mode. Therefore, sensor nodes in the higher density zone will have more opportunity to sleep to achieve the goal of energy balance. As shown in Fig. 2b, in zone (1, 2), there are four sensors in the zone and one sensor at a time stays in active mode in turn to save more power consumption than those sensors deployed in zone (1, 3). Since nodes in zone (1, 2) consume more power than ones in zone (1, 3) for packet forwarding, the energy-balanced goal can be achieved.

Although the proposed approach described above has balanced the power consumption, it may cause packet collision due to the diverse density of sensor deployment. Consequently the MAC Scheduling Phase rules out simultaneous transmissions and receptions of sensor nodes and schedules the transmissions of sensor nodes. To minimize the transmission delay, nodes on the longest path are scheduled first and the scheduling arranges simultaneous transmission as much as possible. Applying the MAC scheduling protocol on the tree shown in Fig. 2a, the scheduling of each node is shown in Fig. 3. For example, node₄ transmits three data packets in time slots 1, 4, and 5 and receives two data packets in time slots 2 and 3.

To extend from a Grid-based WSN to a randomly deployed WSN, this paper integrates the Distance-based and Density-based mechanisms to balance the energy consumption of each sensor in a randomly deployed WSN. Firstly, the Density-based mechanism is adopted to partition the WSN into a number of equal-sized zones according to the geographical information and uses active/sleep scheme to balance the power consumption of

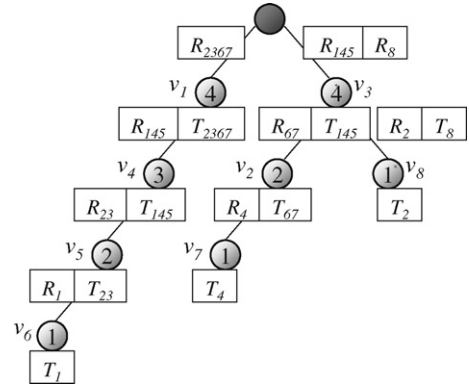


Fig. 3. A tree presentation of Fig. 2a where R_{slots} and T_{slots} respectively denote the slots for sensor receiving and transmitting information.

sensor nodes in each zone. Since sensors are randomly deployed, the density of sensor nodes in each zone may be highly concentrated or too sparse and cannot meet the density required by the Density-based Scheme. Regarding the zone that contains a higher density than the required one, the Power Control mechanism will be further applied by the Distance-based Scheme to make the transmission range of these sensor nodes larger than other zones. Utilizing sensor nodes in a high density zone to relay data packets will decrease the load of sensor nodes in a low density zone, and therefore balance the power consumption of each sensor node in a randomly deployed WSN.

Fig. 4 depicts an example of extending the energy-balanced mechanism from a Grid-based WSN to a randomly deployed WSN. Firstly, the Density-based Scheme is employed to partition the WSNs into a 3×3 Grid-based topology. Each sensor in the zone will stay in active mode in turn. Then the active sensor will follow the black arrow-head to transmit the sensing information to the sink node. According to the Density-based Scheme, the density required in each zone is shown in Fig. 4. For instance, zone A requires three sensors but actually has six sensors. On the contrary, zone B requires four sensors but actually

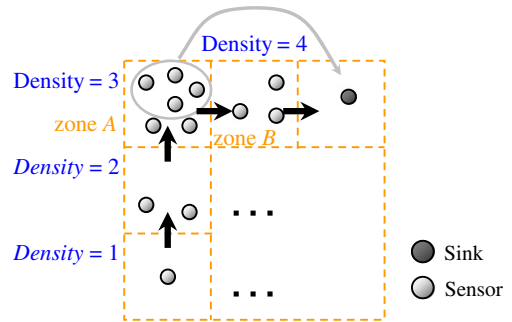


Fig. 4. An example illustrating the extension of the proposed energy-balanced mechanisms from a Grid-based network to a randomly deployed WSN.

has three sensors. Consequently, the Power Control mechanism used in the Density-based Scheme will be applied to enlarge the transmitting power of the 4 sensor nodes in zone A to send a data packet to the sink node directly and eliminate the data relaying traffic of sensor nodes in zone B, balancing the energy consumptions for sensor nodes in zones A and B.

3. Energy-balanced mechanisms

3.1. Topology construction phase

To collect the sensing data from all sensors to the sink node efficiently, an efficient tree is required to provide routing path from each sensor to the sink. The constructed tree will guarantee the *root-balanced* property that the total number of nodes in the left and right subtrees of the root differs at most by one, reducing the time required for collecting sensing information at the sink node. An *L-based* tree construction mechanism is proposed to construct a tree that satisfies the root-balanced property. Because the sink node is deployed at the extremely top right location of a Grid-based WSN, each sensor constructs either right link or up link to its parent in the tree.

As shown in Fig. 5, sensors are partitioned into multiple L-Layer. The tree construction rule is that a right or up link will be established to construct the tree if the sensor is located in the odd or even L-Layer, respectively. For example, sensors belonging to the first L-Layer will establish right links and sensors located at the second L-Layer will establish up links to construct the tree. Here we call the sensors located in the extremely top row and the extremely right column the boundary nodes. According to tree construction rules, the boundary nodes may be unable to transmit data packet to the sink node thanks to their location. As such, boundary nodes in the extremely top row will establish right links whereas boundary nodes in the extremely right column will establish up links. Then these boundary nodes will transmit data packet to the sink node successfully. Fig. 5 depicts the constructed tree according to the described rules. Fig. 6 is a detailed algorithm of the Topology Construction Phase. The constructed tree topology guarantees the root-balanced property.

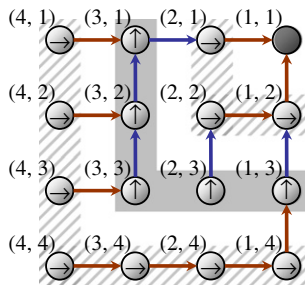


Fig. 5. The shadow region marks the L-Layer partitions. A tree is constructed in the Topology Construction Phase for a 4 × 4 Grid-based WSN.

Algorithm: Topology Construction

Input: the coordinate (x_v, y_v) of node v

Output: parent of node v

1. **case 1:** $(x_v \neq 1 \text{ and } y_v = 1)$
2. direction of link is right ;
3. **case 2:** $(x_v = 1 \text{ and } y_v \neq 1)$
4. direction of link is up ;
5. **case 3:** $(x_v \neq 1 \text{ and } y_v \neq 1)$
6. **if** $(\max\{x_v, y_v\} \text{ is odd})$
7. direction of link is up ;
8. **else**
9. direction of link is right ;
10. **end if**

Fig. 6. Algorithm of Topology Construction Phase.

The following theorem proves that the constructed tree guarantees that the total number of nodes in the left subtree and the right subtree of the sink node differs one at most. Some symbols are defined below. Let $|L(\text{sink})|$ and $|R(\text{sink})|$ respectively denote the number of sensor nodes in the left and right subtrees of the sink node. Let symbols $L_i(\text{sink})$ and $R_i(\text{sink})$ denote the set of sensor nodes belonging to the i th L-Layer of sink node's left subtrees and right subtrees, respectively, and symbols $|L_i(\text{sink})|$ and $|R_i(\text{sink})|$ respectively denote the number of elements in $L_i(\text{sink})$ and $R_i(\text{sink})$. From Fig. 5, it is observed that $|L_1(\text{sink})| = 1$, $|L_2(\text{sink})| = 3$, $|L_3(\text{sink})| = 3$, and so forth. $|L_i(\text{sink})|$ will stand on the sequence $(1, 3, 3, 5, \dots, \lceil \frac{i+1}{2} \rceil \times 2 - 1)$ and $|R_i(\text{sink})|$ will stand on the sequence $(2, 2, 4, 4, 6, \dots, \lceil \frac{i}{2} \rceil \times 2)$. The following theorem verifies that the constructed tree guarantees root-balanced property.

Theorem 1. *The tree constructed in the Tree Construction Phase guarantees that the numbers of nodes in left and right subtrees of the sink node differ one at most.*

Proof. There are totally $N - 1$ L-Layers in an $N \times N$ Grid-based WSN. In case of $N \geq 2$, the number of nodes in the left and right subtrees of the sink node can be derived via the following formula:

$$|L(\text{sink})| = \sum_{i=1}^{N-1} |L_i(\text{sink})| = \sum_{i=1}^{N-1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1,$$

$$|R(\text{sink})| = \sum_{i=1}^{N-1} |R_i(\text{sink})| = \sum_{i=1}^{N-1} \left\lceil \frac{i}{2} \right\rceil \times 2.$$

The following uses mathematical induction to show that the tree is root balanced in both cases that N is odd and N is even.

Case 1 (N is odd).

Base: $N = 3$, $\sum_{i=1}^{N-1} |L_i(\text{sink})| = \sum_{i=1}^2 \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 = 4$,

$$\sum_{i=1}^{N-1} |R_i(\text{sink})| = \sum_{i=1}^2 \left\lceil \frac{i}{2} \right\rceil \times 2 = 4.$$

Hence we have $|L(\text{sink})| = |R(\text{sink})|$. Assume: when $N = k$, $|L(\text{sink})| = |R(\text{sink})|$ is true. That is, $\sum_{i=1}^{k-1} |L_i(\text{sink})| = \sum_{i=1}^{k-1} |R_i(\text{sink})|$. Therefore, $\sum_{i=1}^{k-1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 = \sum_{i=1}^{k-1} \left\lceil \frac{i}{2} \right\rceil \times 2$. When $N = k+2$,

$$\begin{aligned}
\sum_{i=1}^{N-1} |L_i(\text{sink})| &= \sum_{i=1}^{k+1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 - 1 \right) \\
&\quad + \left(\left\lceil \frac{(k+1)+1}{2} \right\rceil \times 2 - 1 \right), \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i}{2} \right\rceil \times 2 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 - 1 \right) \\
&\quad + \left(\left\lceil \frac{k}{2} \right\rceil \times 2 + 2 - 1 \right) \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i}{2} \right\rceil \times 2 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 \right) + \left(\left\lceil \frac{k}{2} \right\rceil \times 2 \right), \\
&= \sum_{i=1}^{k+1} \left\lceil \frac{i}{2} \right\rceil \times 2 = \sum_{i=1}^{k+1} |R_i(\text{sink})|.
\end{aligned}$$

Consequently, $|L(\text{sink})| = |R(\text{sink})|$ in case that N is odd.

Case 2 (N is even). Base: $N = 2$, $\sum_{i=1}^{N-1} |L_i(\text{sink})| = \sum_{i=1}^1 \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 = 1$

$$\sum_{i=1}^{N-1} |R_i(\text{sink})| = \sum_{i=1}^1 \left\lceil \frac{i}{2} \right\rceil \times 2 = 2$$

$||L(\text{sink})| - |R(\text{sink})|| = 1$. Assume: when $N = k$, $||L(\text{sink})| - |R(\text{sink})|| = 1$ is true. When $N = k + 2$,

$$\begin{aligned}
\sum_{i=1}^{N-1} |L_i(\text{sink})| &= \sum_{i=1}^{k+1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1, \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 - 1 \right) \\
&\quad + \left(\left\lceil \frac{(k+1)+1}{2} \right\rceil \times 2 - 1 \right) \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i}{2} \right\rceil \times 2 - 1 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 - 1 \right) \\
&\quad + \left(\left\lceil \frac{k}{2} \right\rceil \times 2 + 1 \right), \\
&= \sum_{i=1}^{k-1} \left\lceil \frac{i}{2} \right\rceil \times 2 + \left(\left\lceil \frac{k+1}{2} \right\rceil \times 2 \right) \\
&\quad + \left(\left\lceil \frac{k}{2} \right\rceil \times 2 \right) - 1 = \sum_{i=1}^{k+1} \left\lceil \frac{i}{2} \right\rceil \times 2 - 1 \\
&= \sum_{i=1}^{k+1} |R_i(\text{sink})| - 1.
\end{aligned}$$

As it turns out, $||L(\text{sink})| - |R(\text{sink})|| = 1$ when N is even. From mathematical induction, the following relations between $|L(\text{sink})|$ and $|R(\text{sink})|$ are proved. $\square$

$$\begin{cases} N \text{ is odd, } |L(\text{sink})| = |R(\text{sink})|, \\ N \text{ is even, } ||L(\text{sink})| - |R(\text{sink})|| = 1. \end{cases}$$

From the proof of [Theorem 1](#), the constructed tree guarantees that the numbers of nodes in the sink node's left and right subtrees differ one at most. The constructed tree helps reduce the delay time for data gathering in a WSN.

3.2. Node placement phase

After constructing a root-balanced tree, the sink will calculate the number of packet forwarding required by

each sensor. According to different forwarding load, Distance-based and Density-based node placement mechanisms are proposed to balance the energy consumption of each sensor node.

3.2.1. Number of forwarding packet

This paper assumes that each sensor node will generate one data packet within a constant period of time and all sensor nodes have the same initial energy. Sensors closer to the sink node will have heavier packets forwarding load. Therefore, the forwarding load of each sensor is location-dependent and will be derived based on its position in the constructed tree. The location of sensors in the tree will be categorized into six cases: (1) top boundary nodes; (2) right boundary nodes; (3) nodes on the diagonal line; (4) leaf nodes; (5) nodes above the diagonal line and (6) nodes below the diagonal line. Let $T(x_v, y_v)$ denotes the forwarding load of a sensor with coordinate (x_v, y_v) . The following derives $T(x_v, y_v)$ for each case.

3.2.1.1. The forwarding load of the top boundary nodes. As [Fig. 7](#) indicates, $|L_i(\text{sink})|$ increases with i according to the sequence $(1, 3, 3, 5, 5, \dots, \left\lceil \frac{i+1}{2} \right\rceil \times 2 - 1)$. The value i and the coordinates of sensor nodes which are located on the i th Layer have the relations $x_v - 1 = i$ and $y_v - 1 = i$. In addition, the sensor node that locates on the odd L-Layer has the forwarding load of $1 + \sum_{j=i+1}^{N-1} |L_j(\text{sink})|$. On the other hand, the sensor node that locates on the even L-Layer has the forwarding load of $0 + \sum_{j=i+0}^{N-1} |L_j(\text{sink})|$. We use $i \bmod 2 = 1$ to represent the sensor nodes on the odd L-Layer and $i \bmod 2 = 0$ to represent the sensor node on the even L-Layer. Consequently, the forwarding load of the top boundary nodes is given by formula (1).

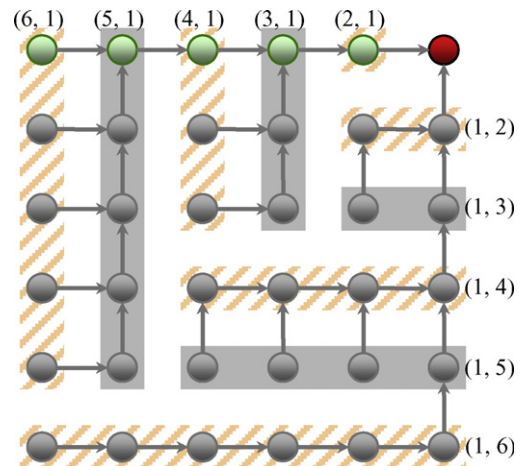


Fig. 7. An example of 6 × 6 Grid-based network shows that $|L_i(\text{sink})|$ increases with i according to the sequence $(1, 3, 3, 5, 5, \dots)$ and $|R_i(\text{sink})|$ increases with i according to the sequence $(2, 2, 4, 4, 6, \dots)$.

$$\begin{aligned}
T(x_v, y_v) &= (i \bmod 2) + \sum_{j=i+(i \bmod 2)}^{N-1} |L_j(\text{sink})| \\
&= (i \bmod 2) + \sum_{j=i+(i \bmod 2)}^{N-1} \left\lceil \frac{j+1}{2} \right\rceil \times 2 - 1, \Rightarrow T(x_v, y_v) \\
&= ((x_v - 1) \bmod 2) \\
&\quad + \sum_{j=x_v-1+((x_v-1) \bmod 2)}^{N-1} \left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - 1 \right), \\
&\text{if } x_v \neq 1 \text{ and } y_v = 1.
\end{aligned} \quad (1)$$

3.2.1.2. The forwarding load of the right boundary nodes. As Fig. 7 shows, $|R_i(\text{sink})|$ increases with i according to the sequence $(2, 2, 4, 4, 6, \dots, \lceil \frac{i}{2} \rceil \times 2)$. The value i and the coordinates of sensor nodes which are located on the i th Layer have the relation $y_v - 1 = i$. In addition, the sensor node that locates on the even and odd L-Layer has the forwarding load $1 + \sum_{j=i+1}^{N-1} |R_j(\text{sink})|$ and $0 + \sum_{j=i+0}^{N-1} |R_j(\text{sink})|$, respectively. The forwarding load of the right boundary nodes is obtained by formula (2) as derived in below.

$$\begin{aligned}
T(x_v, y_v) &= ((i+1) \bmod 2) + \sum_{j=i+((i+1) \bmod 2)}^{N-1} |R_j(\text{sink})| \\
&= ((i+1) \bmod 2) + \sum_{j=i+((i+1) \bmod 2)}^{N-1} \left\lceil \frac{j}{2} \right\rceil \times 2, \\
\Rightarrow T(x_v, y_v) &= (y_v \bmod 2) + \sum_{j=y_v-1+(y_v \bmod 2)}^{N-1} \left(\left\lceil \frac{j}{2} \right\rceil \times 2 \right), \\
&\text{if } x_v = 1 \text{ and } y_v \neq 1.
\end{aligned} \quad (2)$$

Fig. 7 depicts an example to illustrate the forwarding load of the top boundary and right boundary nodes. Take the sensor node with coordinate $(4, 1)$ in a 6×6 Grid-based tree topology, for example. The forwarding load $T(4, 1)$ is $1 + \sum_{j=4}^5 \left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - 1 \right) = 1 + 5 + 5 = 11$. Similarly, the forwarding load of the sensor node with coordinate $(3, 1)$ is $T(3, 1) = 0 + 3 + 3 + 5 + 5 = 16$. Moreover, the sensor node with coordinate $(3, 1)$ has $T(1, 3) = 1 + 4 + 4 + 6 = 15$ forwarding load and the sensor node with coordinate $(1, 4)$ has $T(1, 4) = 0 + 4 + 4 + 6 = 14$ forwarding load. These exam-

ples also verify that the forwarding load derived for each sensor equals the number of nodes in the subtrees rooted by this sensor.

3.2.1.3. The forwarding load of the nodes on the diagonal line. Fig. 8a shows that the sensor nodes on the diagonal line need to forward two data packets except the sensor node with coordinate (N, N) . The sensor node deployed on the coordinate (N, N) only has forwarding load of one data packet. Therefore the following generalizes the forwarding load of sensor nodes on the diagonal line.

$$\begin{aligned}
T(x_v, y_v) &= 2, & \text{if } (x_v = y_v \neq 1) \text{ and } (x_v = y_v \neq N), \\
T(x_v, y_v) &= 1, & \text{if } (x_v = y_v = N).
\end{aligned} \quad (3)$$

3.2.1.4. The forwarding load of leaf nodes. Fig. 8b also indicates the following facts. The sensor nodes that are located above the diagonal line and are deployed on the odd L-Layer will become a leaf node. Similarly, the sensor nodes that are located below the diagonal line and are deployed on the even L-Layer will become a leaf node. Since the leaf node only need to transmit one data packet, which is its own sensing information, formula (5) reflects this fact.

$$\begin{aligned}
&\text{if } (x_v \neq 1 \wedge y_v \neq 1) \text{ and } (x_v > y_v) \\
&\quad \text{and } (x_v \text{ is even}), \\
T(x_v, y_v) &= 1, & \text{if } (x_v \neq 1 \wedge y_v \neq 1) \text{ and } (x_v < y_v) \\
&\quad \text{and } (y_v \text{ is odd}).
\end{aligned} \quad (5)$$

3.2.1.5. The forwarding load of the nodes above the diagonal line (except the leaf nodes and nodes located on the x -axis). Assume that node v is located above the diagonal line but it is neither a leaf node nor a top boundary node. Furthermore, assume that node v belongs to the i th L-Layer. Nodes that are rooted by node v can be characterized to be located on either i th or $(i+1)$ th L-Layer. Therefore, the forwarding load of node v only requires the counting of the number of those nodes that are rooted by itself from i th L-Layer to the $\min\{i+1, N-1\}$ th L-Layer.

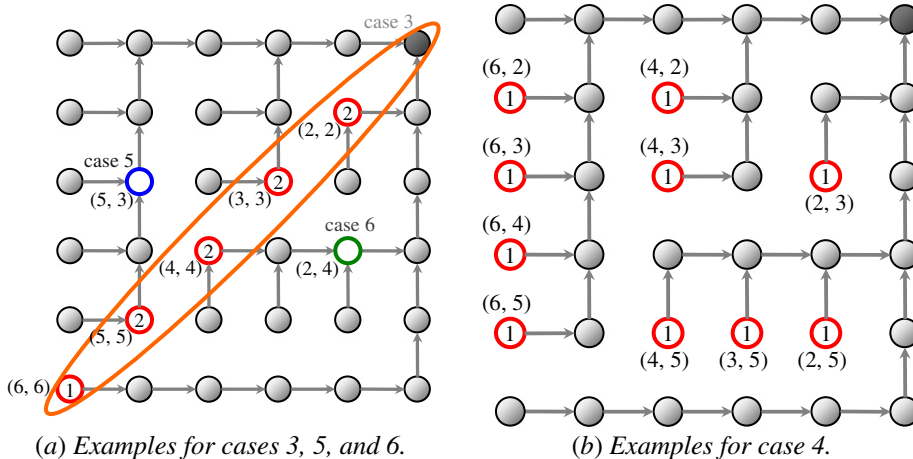


Fig. 8. Examples to show the forwarding load of each node in cases 3, 4, 5, and 6. (a) Examples for cases 3, 5, and 6. (b) Examples for case 4.

Let $n_{x,i}$ denote the number of nodes that are rooted by x and locate on the i th L-Layer in the tree. Consequently, the forwarding load of node v can be obtained by $n_{v,i} + n_{v,i+1}$. The value of $n_{v,i}$ can be derived from $n_{k,i}$ where k denotes the top boundary node on the same Layer. It stands that $n_{v,i} = n_{k,i} - (y_v - 1)$. Hence the forwarding load of node v can be calculated by Eq. (6) as shown in below.

$$\begin{aligned}
 T(x_v, y_v) &= \sum_{j=i}^{\min\{i+1, N-1\}} \left(\left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - 1 \right) - (y_v - 1) \right) \\
 &= \sum_{j=x_v-1}^{\min\{x_v, N-1\}} \left(\left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - 1 \right) - (y_v - 1) \right), \\
 &\Rightarrow T(x_v, y_v) = \sum_{j=x_v-1}^{\min\{x_v, N-1\}} \left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - y_v \right), \\
 &\quad \text{if } (x_v \neq 1 \wedge y_v \neq 1) \text{ and } (x_v > y_v) \text{ and } (x_v \text{ is odd}).
 \end{aligned} \tag{6}$$

3.2.1.6. The forwarding load of the nodes below the diagonal line (except the leaf nodes and the nodes located on the y -axis). Similar to formula (6), the forwarding load of nodes below the diagonal line can be derived as shown in formula (7).

$$\begin{aligned}
 T(x_v, y_v) &= \sum_{j=i}^{\min\{i+1, N-1\}} \left(\left\lceil \frac{j}{2} \right\rceil \times 2 - (x_v - 1) \right) \\
 &= \sum_{j=y_v-1}^{\min\{y_v, N-1\}} \left(\left\lceil \frac{j}{2} \right\rceil \times 2 - (x_v - 1) \right), \\
 &\Rightarrow T(x_v, y_v) = \sum_{j=y_v-1}^{\min\{y_v, N-1\}} \left(\left\lceil \frac{j}{2} \right\rceil \times 2 - x_v + 1 \right), \\
 &\quad \text{if } (x_v \neq 1 \wedge y_v \neq 1) \text{ and } (x_v < y_v) \text{ and } (y_v \text{ is even}).
 \end{aligned} \tag{7}$$

Fig. 8a depicts an example that illustrates the forwarding load of nodes above and below the diagonal line. According to formula (6), the forwarding load of the sensor node located on the coordinate (5, 3) is

$$T(5, 3) = \sum_{j=4}^{\min\{5, 5\}} \left(\left\lceil \frac{j+1}{2} \right\rceil \times 2 - 3 \right) = 3 + 3 = 6.$$

3.2.2. Distance-based scheme

The sensor nodes closer to the sink node have a heavier traffic load. The Distance-based scheme adjusts each sensor node's location according to its forwarding traffic load. Sensors that are closer to the sink node will be placed with a smaller distance to its parent. Then, the power control mechanism is applied to save the power consumption of those sensor nodes with a heavy forwarding load and hence balances all sensor nodes' power consumption.

Let $T(x_u, y_u)$ denotes the forwarding load of sensor node u and P_u denotes its power consumption for each data transmission. To balance the power consumption of arbitrary two sensor nodes u and v , the following equation should be held.

$$P_v \times T(x_v, y_v) = P_u \times T(x_u, y_u). \tag{8}$$

Let d_u represent the distance between node u and its parent. For a sender to transmit to a receiver a stream of data at rate R , the corresponding transmission power P can be modeled as $P = R^\alpha d^\alpha$ [13], where $2 \leq \alpha \leq 4$ is the path loss exponent, depending on different channel models. Eq. (9) depicts the relation between transmission distance and forwarding load.

$$d_v^\alpha \times T(x_v, y_v) = d_u^\alpha \times T(x_u, y_u) \Rightarrow d_v = \sqrt[\alpha]{\frac{T(x_u, y_u)}{T(x_v, y_v)}} \times d_u \tag{9}$$

Eq. (9) reflects the observation that the sensor node with heavier forwarding traffic load has smaller transmission distance to its parent and therefore the power consumption of each sensor node can be balanced. Let all sensors have identical sensing range d_s . To achieve the full coverage with the minimal number of sensors, sensors should be deployed with a distance of $\sqrt{3}d_s$ from its neighbors. Therefore the communication range is at least $\sqrt{3}d_s$. Let u be the sensor node with the largest distance to the sink node in a WSN. To minimize the number of deployed sensor nodes in the WSN, we grant the distance between node u and Parent(u) is the largest distance in the WSN. In other words, d_u is equal to $\sqrt{3}d_s$. The Eq. (10) can derive the distance between any node v and its parent where $T(x_v, y_v)$ can be calculated by Eqs. (1)–(7). Since the forwarding load of node u is one, the power consumption of node u is proportional to $d_u^2 \times 1$. Therefore, any sensor node v that intends to balance its power consumption with node u should satisfy Eq. (10).

$$\begin{aligned}
 d_v^\alpha \times T(x_v, y_v) &= d_u^\alpha \times T(x_u, y_u) = d_u^\alpha \times 1 \\
 \Rightarrow d_v &= \sqrt[\alpha]{\frac{du}{T(x_v, y_v)}}
 \end{aligned} \tag{10}$$

Consider an example shown in Fig. 2a. Let $u = v_6$ and $v = v_1$. The forwarding load of nodes u and v are $T(x_u, y_u) = 1$ and $T(x_v, y_v) = 4$ respectively according to Eqs. (1)–(7). The number labeled on the node represents the forwarding load of that node. Assume that the sensing range d_s is 20 meters and the communication range d is 40 meters. Since node u is the farthest node away from the sink, the distance from itself to its parent can be the largest. To achieve the full coverage purpose, d_u can be set at $20\sqrt{3}$ meters. According to Eq. (10), sensor node v should be deployed with a distance $\sqrt[\alpha]{\frac{T(x_u, y_u)=1}{T(x_v, y_v)=4}} d_s$ to its parent node Parent(v) and the transmission distance of sensor node v is controlled by $\sqrt[\alpha]{\frac{T(x_u, y_u)=1}{T(x_v, y_v)=4}} d_s$ meters using the power control scheme. As a result, the power control mechanism will balance the energy consumption of the sensor nodes u and v .

3.2.3. Density-based scheme

In addition to the Distance-based scheme, another mechanism, namely *Density-based Scheme*, is presented to balance the power consumption of sensor nodes. The basic idea of Density-based Scheme is that we partition the monitoring region into several equal-sized zones. Then we arrange each zone with different number of sensors according to the zone's forwarding load. That is, for those zones closer to the sink node, the Density-based Scheme

arranges more sensors and applies the sleep-and-wakeup strategy to balance their power consumption. Although zones closer to the sink node have an unfavorable situation in forwarding load, placing more sensors in the zone and arranging one of them in the active state in turn will save more power to balance the unfavorable situation in power consumption.

For each zone, there is exactly one sensor node staying in active mode to be responsible for transmitting or forwarding the packet to the parent zone. In the Density-based Scheme, each zone will be virtually treated as a node in the tree. This scheme uses a zone as a unit and employs the tree constructed in the Topology Construction Phase as the routing path for sensors transmitting the sensing information to the sink node. The size of each zone should be controlled in order to maintain the full coverage. Consider a WSN that has been partitioned into $N \times N$ zones and each zone has been placed at least one sensor. To guarantee the full coverage, the diagonal length of a zone should equal the sensing range d_s . Therefore, even though the worst case occurs that the active sensor is located at the corner of its zone, its sensing range can also cover that zone. This can guarantee that any active sensor located in any place of that zone can meet the full coverage requirement. Therefore the edge length of each zone should be $(1/\sqrt{2})d_s$. To allow that any two sensors belonging to two neighboring zones are within the communication range, the transmission range should satisfy $d \geq (\sqrt{5}/\sqrt{2})d_s$.

Different to the Distance-based Scheme, the transmission power in the Density-based Scheme is fixed. However, each sensor node in a zone will stay in active state in turn. That is, if there are k sensors in a zone, each sensor will serve for one period of time and the other $k-1$ sensors stay in sleep mode in this period for power saving. There are already lots of existing works focusing on how to establish clusters and provide some approaches to choose cluster header [11,12]. The active sensor acts similar to the cluster header and therefore we are not discussing how to change a sensor node from the sleep state to the active state.

Based on the abovementioned constraint, the following discusses the number of deployed sensors for each zone. Assume that sensor nodes u and v are located in zones A and B , respectively. Let $T(Z)$ denote the forwarding load of zone Z in the tree constructed in the Topology Construction Phase. Therefore, zones A and B have forwarding load $T(A)$ and $T(B)$, respectively. Furthermore, let $\text{Density}(A)$ and $\text{Density}(B)$ denote the deployment density of zones A and B , respectively. To balance the power consumption of sensor nodes in the two zones, requirement specified in formula (11) should be satisfied.

$$\text{Density}(A) = T(A) \quad \text{and} \quad \text{Density}(B) = T(B). \quad (11)$$

Let Z_w be the zone with the largest distance to the sink node in a WSN. To minimize the number of deployed sensor nodes in the WSN, we set $\text{Density}(Z_w) = 1$ since the forwarding load of Z_w is $T(Z_w) = 1$. According to formula (1)–(7), the forwarding load of any zone Z other than Z_w can be derived and is denoted by $T(Z)$. To balance the power consumption, the density of zone Z should equal to $T(Z)$. For example, consider Fig. 2b. Let zones A and B be the two zones with coordinates $(3, 3)$ and $(2, 1)$, respectively. The forwarding loads of

zones A and B are $T(A) = 1$ and $T(B) = 4$, respectively. According to formula (1)–(7), we deploy $\text{Density}(A) = 1$ sensor in zone A and $\text{Density}(B) = 4$ sensors in zone B . Then one of the four sensors in zone B may stay in active mode in turn and the other three sensors may stay in sleep mode to save their power consumption. Therefore, sensors in zones A and B will have the same lifetime.

The proposed Distance-based and Density-based Schemes try to adaptively change the distance or the density of the node deployment. The distinction between Distance-based and Density-based Schemes is that the Distance-based Scheme controls the distance of node placement and adopts power control mechanism to balance the energy consumption while the Density-based Scheme controls the number of sensors deployed in each zone and adopts sleep-wakeup mechanism to balance the energy consumption.

3.3. MAC scheduling phase

This subsection proposes MAC Scheduling to prevent the transmission of sensor nodes from collision and exploit the opportunities for simultaneous transmissions. An existing collision indicates a receiver's location is within the communication range of more than one sender and those senders transmit data to their parents simultaneously. These sensors can be denoted as a *collision set* and the MAC scheduling may arrange sensors in each collision set in different time slots. The following firstly discusses how to derive the physical location of each sensor in a recursive manner. Then the physical locations of sensors will be used to calculate the collision set of each sensor node. The scheduling mechanism will be addressed based on the deployment result by applying the Distance-based Scheme. A collision-free MAC scheduling also can be similarly designed based on the proposed Density-based Scheme.

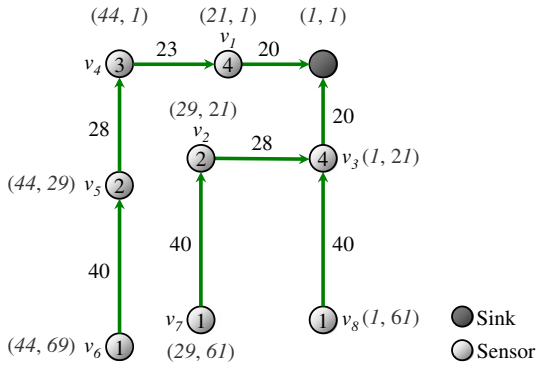
Since the Distance-based Scheme changes the node placement in the grid, the distances of different pairs are different and the Grid-based topology has been twisted. In the following, the physical coordinate of each sensor will be derived. Given a coordinate (x_v, y_v) in the original Grid-based network, the physical coordinate after applying Distance-based Scheme is denoted by (x'_v, y'_v) . Fig. 9 depicts the algorithm that transforms (x_v, y_v) to (x'_v, y'_v) .

According to the link direction, v_6 executes lines 5–7 of *Calculate_Physical_Coordinate* algorithm to evaluate its physical coordinate, as shown in Fig. 10. At first, v_6 calculates the physical coordinate of its parent node v_5 . By applying the Distance-based Scheme, d_{v_6} is 40. Finally, we obtain the v_6 's physical coordinate $(x'_{v_6}, y'_{v_6}) = (x'_{v_5}, y'_{v_5}) + (0, 40) = (44, 69)$. Similarly, the physical coordinate of other sensor nodes can be evaluated.

Since an internal node, say v , in the constructed tree may have several children nodes, node v may be allocated more than one time slots for receiving or forwarding data. Let one dimensional array $v.\text{Transmitting}[i]$ and $v.\text{Receiving}[i]$ respectively denote the transmitting and receiving states of node v in slot i , where $1 \leq i \leq m$. Initially, the values of $v.\text{Transmitting}[i]$ and $v.\text{Receiving}[i]$ are NULL. If the MAC scheduling grants node v to transmit packet in

Algorithm: Calculate_Physical_Coordinate**Input:** the coordinate (x_v, y_v) of node v **Output:** the physical coordinate (x'_v, y'_v) of node v

1. **if** ($x_v \neq 1$ or $y_v \neq 1$)
2. **if** (direction of link of (x_v, y_v) is $\rightarrow$)
3. $(x'_v, y'_v) =$
 Calculate_Physical_Coordinate $(x_{parent(v)}, y_{parent(v)}) + (d / \sqrt[q]{T(x_v, y_v)}, 0)$;
4. **end if**
5. **if** (direction of link of (x_v, y_v) is $\uparrow$)
6. $(x'_v, y'_v) =$
 Calculate_Physical_Coordinate $(x_{parent(v)}, y_{parent(v)}) + (0, d / \sqrt[q]{T(x_v, y_v)})$;
7. **end if**
8. **end if**
9. **else**
10. return (1, 1);
11. **end if**

Fig. 9. Algorithm that transforms a logical coordinate in Grid-based topology to a physical coordinate.**Fig. 10.** An example of calculating the physical coordinate.

slot i , the value of $v_Transmitting[i]$ will be set by 1. Otherwise, the value of $v_Transmitting[i]$ will be set by 0. Similarly, if the MAC scheduling grants node v to receive packet in slot i , the value of $v_Receiving[i]$ will be set by 1. Otherwise, the value of $v_Receiving[i]$ will be set by 0. In case that both $v_Transmitting[i]$ and $v_Receiving[i]$ have value 0, node v will sleep in slot i . One essential task of developing a collision-free MAC scheduling is to derive those nodes whose transmissions will interfere with node v 's data receiving. Expression (12) examines if node u 's transmission interferes with node v 's data receiving.

$$(x'_u - x'_v)^2 + (y'_u - y'_v)^2 \leq \left(\frac{d}{\sqrt[q]{T(x_u, y_u)}} \right)^2. \quad (12)$$

In case that the coordinates of nodes u and v satisfy expression (12), node v is within node u 's transmitting range. Let *collision set*, denoted by C_v , represent the set of nodes that satisfy expression (12).

Since the longest path in a tree usually causes the bottleneck of the end-to-end delay, nodes in the longest path will be scheduled first, in an order from leaf node to the sink node. Fig. 11 depicts the proposed MAC_Scheduling algorithm where valuable *count* evaluates the forwarding load of sensor node v , including transmitting and receiving data packets. Let v be the leaf node and u be v 's parent in the con-

Algorithm: MAC_Scheduling for Sensor Node v **Input:** (x_v, y_v) , (x_u, y_u) , $T(v)$, where node u is node v 's parent**Output:** Schedule for transmission of node v and receiving of node u

1. **int** count = $T(v)$;
2. **int** $i=1$;
3. **While**(count!=0)
4. **if** ($v_Transmitting[i] = \text{NULL}$ && $u_Receiving[i] = \text{NULL}$)
5. set $v_Transmitting[i] = 1$;
6. set $u_Receiving[i] = 1$;
7. set $v_Receiving[i] = 0$;
8. set $u_Transmitting[i] = 0$;
9. **for all** ($p \in R_v - \{u\}$)
10. set $p_Receiving[i] = 0$;
11. **for all** ($q \in C_u - \{v\}$)
12. set $q_Transmitting[i] = 0$;
13. count = count - 1;
14. $i=i+1$;
15. **else if**
16. $i=i+1$;
17. **end if**
18. **end while**

Fig. 11. Collision-free MAC scheduling algorithm.

structed tree. At first, the i th slot is checked if $v_Transmitting[i]$ and $u_Receiving[i]$ are NULL. If a time slot, say k , has Null value to both $v_Transmitting[k]$ and $u_Receiving[k]$, it means that sensor node v can transmit data packet to its parent node u . Line 5 sets $v_Transmitting[k] = 1$ and line 6 sets $u_Receiving[k] = 1$. Since node v cannot receive while it transmits data, line 7 sets the $v_Receiving[k] = 0$. Similarly, line 8 sets the $u_Transmitting[k] = 0$. Let receiving set, denoted by R_u , represent the set of nodes that are within node u 's transmission range. Noted that if $u \in C_v$ then $v \in R_u$. To ensure the other sensor nodes rather than u and v are scheduled without collision, all sensor nodes in set $R_v - \{u\}$ cannot receive data in slot k . Lines 9 and 10 of Fig. 13 depict that $p_Receiving[i] = 0$ for all $p \in R_v - \{u\}$. Similarly, lines 11 and 12 set $q_Transmitting[i] = 0$ for all $q \in C_u - \{v\}$.

Since a time slot can transmit only one data packet, lines 4–17 will be repeated if sensor node v intends to forward many packets until all forwarding data packets of node v are scheduled. Then the algorithm continues to

schedule the transmitting slots of parent node u . As all sensor nodes in this path are scheduled, we will choose the second longest path and schedule each node on the path according to the algorithm depicted in Fig. 11. The algorithm will stop if all nodes have been scheduled.

Take Fig. 3 as an example. The collision set and receiving set of each sensor node is shown in below.

$$\begin{aligned}
 C_{\text{sink}} &= \{v_1, v_3\} & C_{v5} &= \{v_2, v_6, v_7\} \\
 C_{v1} &= \{v_2, v_4\} & C_{v6} &= \{-\} \\
 C_{v2} &= \{v_5, v_7\} & C_{v7} &= \{-\} \\
 C_{v3} &= \{v_2, v_8\} & C_{v8} &= \{-\} \\
 C_{v4} &= \{v_2, v_5\} & & \\
 R_{\text{sink}} &= \{-\} & R_{v5} &= \{v_2, v_4\}, \\
 R_{v1} &= \{\text{sink}\} & R_{v6} &= \{v_5\}, \\
 R_{v2} &= \{v_1, v_3, v_4, v_5\} & R_{v7} &= \{v_2, v_5\}, \\
 R_{v3} &= \{\text{sink}\} & R_{v8} &= \{v_3\}, \\
 & & R_{v4} &= \{v_1\}.
 \end{aligned}$$

The longest path in the constructed tree is $v_6 \rightarrow v_5 \rightarrow v_4 \rightarrow v_1 \rightarrow \text{Sink Node}$ and therefore node v_6 will be scheduled first. Since values of $v_6.\text{Transmitting}[1]$ and $v_5.\text{Receiving}[1]$ are NULL, lines 5 and 6 of the algorithm set $v_6.\text{Transmitting}[1] = 1$ and the $v_5.\text{Receiving}[1] = 1$ and lines 7 and 8 set $v_6.\text{Receiving}[1] = 0$ and $v_5.\text{Transmitting}[1] = 0$. To avoid other receivers from incurring interference in time slot 1, the sensor nodes in set $R_{v6} - \{\text{Parent}(v_6)\}$ cannot receive data packet in the first time slot. Since $R_{v6} - \{v_5\} = \emptyset$, none of the sensor nodes are settled non-receiving. Further, to avoid the receiver v_5 to be interfered, sensor nodes in $C_{v5} - \{v_6\} = \{v_2, v_7\}$ cannot send data packet in the first time slot, resulting $v_2.\text{Transmitting}[1] = 0$ and $v_7.\text{Transmitting}[1] = 0$.

After scheduling node v_6 , node v_5 is scheduled next. Since values of $v_5.\text{Transmitting}[2]$ and $v_4.\text{Receiving}[2]$ are NULL, lines 5–8 set $v_5.\text{Transmitting}[2] = 1$, $v_4.\text{Receiving}[2] = 1$, $v_5.\text{Receiving}[2] = 0$ and $v_4.\text{Transmitting}[2] = 0$. In addition, lines 9–12 check set $R_{v5} - \{\text{Parent}(v_5)\} = R_{v5} - \{v_4\} = v_2$ and $C_{v4} - \{v_5\} = v_2$ and set $v_2.\text{Receiving}[2] = 0$ and $v_2.\text{Transmitting}[2] = 0$. Since v_5 demands for transmitting two data packets, the scheduling of the second forwarding packet is executed similarly. Finally, all sensor nodes can be subsequently scheduled as shown in Fig. 3.

After applying the proposed MAC scheduling on all sensor nodes, the sink node can receive sensing information from all sensor nodes in eight time slots as shown in Fig. 3. Nodes v_6 and v_4 transmit data packet to their parent nodes simultaneously. Nodes v_5 and v_1 also transmit data packet to their parent nodes in time slots 2 and 3 at the same time. Furthermore, nodes v_4 and v_7 transmit data packet to their parent nodes in time slot 4 simultaneously. The proposed algorithm reduces data transmission delay and prevents the data transmission from collision as well.

4. Extending Grid-based WSNs to randomly deployed WSNs

This section aims to generalize the proposed energy-balanced mechanisms from a Grid-based network to a randomly deployed network. The proposed Distance-based

and Density-based schemes can only be used in the network deployment phase. This section aims to make extension of the developed energy-balanced schemes so that they can be used in communication phase for a randomly deployed network. However, extension from a Grid-based network to a randomly deployed network will encounter the problem that the density and the distance of sensor nodes in the randomly deployed WSNs are unexpected. This section proposes a Hybrid energy-balanced mechanism that integrates the Distance-based Scheme and Density-based Scheme to balance the power consumption of sensors in a randomly deployed WSN. The basic idea behind the proposed algorithm is that we firstly partition the network into several equal-sized zones according to a predefined zone size and then apply Density-based scheme to evaluate the expected density for each zone. Since the density of a randomly deployed WSN can be different with the expected density, the Distance-based scheme is further applied so that zones with a higher density consume more power by using power control mechanism to save the power consumption of the neighboring zones that are deployed with a lower density. Here we call this mechanism as the *Hybrid* scheme.

We partition the randomly deployed WSNs into $N \times N$ equal-sized zones according to the geographical location. This structure will have $N^2 - 1$ zones without considering the zone that the sink node is located. Let d represents the sensor's communication range. To enable sensor nodes in a zone can communicate with all the other sensor nodes in the four neighboring zones (i.e. the above, below, left and right zones), the edge length of a zone should be smaller than or equal to $d/\sqrt{5}$.

Let symbol $Z_{x,y}$ denote the zone located on (x, y) location. Let $R_{x,y}$ and $D_{x,y}$ respectively denote the actual number and ideal number of sensor nodes in zone $Z_{x,y}$. After partitioning the WSNs, a tree will be constructed in the Topology Construction Phase. Let $\text{Left}(Z_{x,y})$, $\text{Right}(Z_{x,y})$ and

Algorithm: Extending to a Randomly Deployed WSN

1. if ($R_{x,y} < D_{x,y}$)
2. if ($\frac{R_{\text{Left}(Z_{x,y})} - D_{\text{Left}(Z_{x,y})}}{2^\alpha} \geq 1$)
3. int help = $\frac{R_{\text{Left}(Z_{x,y})} - D_{\text{Left}(Z_{x,y})}}{2^\alpha}$;
4. $D_{x,y} = D_{x,y} - \text{help}$;
5. if ($R_{x,y} < D_{x,y}$)
6. if ($\frac{R_{\text{Right}(Z_{x,y})} - D_{\text{Right}(Z_{x,y})}}{2^\alpha} \geq 1$)
7. help = $\frac{R_{\text{Right}(Z_{x,y})} - D_{\text{Right}(Z_{x,y})}}{2^\alpha}$;
8. $D_{x,y} = D_{x,y} - \text{help}$;
9. end if
10. end if
11. end if
12. end if

Fig. 12. Algorithm for extending a Grid-based WSN to a randomly deployed WSN.

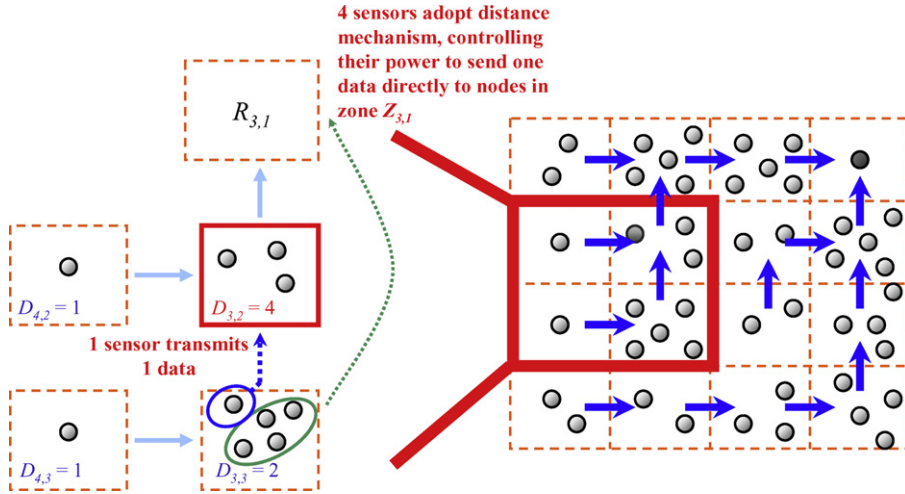


Fig. 13. An example of integrating Density-based and Distance-based Schemes for a randomly deployed WSN.

$\text{Parent}(Z_{x,y})$ respectively denote the left-child zone, right-child zone, and parent zone of zone $Z_{x,y}$ in the tree. To balance the energy consumption for a randomly deployed network, the Density-based Scheme is firstly applied to determine the ideal number $D_{x,y}$ of sensor nodes in zone $Z_{x,y}$ according to the distance from the zone to the sink node. Then the Distance-based Scheme is adopted to solve the problem that the actual number of sensor nodes in the zone $Z_{x,y}$ cannot meet the ideal density. In case that $R_{x,y} < D_{x,y}$, the number of sensor nodes in $Z_{x,y}$ is not enough to transmit all sensing information to the node in the parent zone. Therefore the basic idea is to reduce the forwarding load of $Z_{x,y}$. We look for superfluous sensor nodes from $\text{Left}(Z_{x,y})$ and $\text{Right}(Z_{x,y})$ to help $Z_{x,y}$ forward data packets to $\text{Parent}(Z_{x,y})$ by applying the power control mechanism. Because that the power consumption is proportional to the α power of distance and the distance between the child zone of $Z_{x,y}$ and $\text{Parent}(Z_{x,y})$ is 2 hops, therefore the power consumption that the child zone forwards one data packet to $\text{Parent}(Z_{x,y})$ is a multiple of 2^α .

The algorithm for extending the energy-balanced mechanisms from a Grid-based WSN to a randomly deployed WSN is shown in Fig. 12. Lines 2–4 determine whether $\text{Left}(Z_{x,y})$ has superfluous sensor node to help $Z_{x,y}$ forward data packet to $\text{Parent}(Z_{x,y})$. Lines 6 to 8 determine whether or not $\text{Right}(Z_{x,y})$ has superfluous sensor nodes to help $Z_{x,y}$ forward data packet to $\text{Parent}(Z_{x,y})$. To accomplish this, the sink node should collect the location information of each sensor and then applies the algorithm shown in Fig. 12 to each of those zones where the number of sensors in that zone is smaller than the ideal number of that zone.

Take Fig. 13 as an example. The Density-based Scheme is employed to partition the WSN into a 4×4 Grid-based network and links between zones are established by applying L-based Tree Construction mechanism. To explain the mechanism in detail, we focus on the zones $Z_{3,2}$, $Z_{3,3}$, $Z_{4,2}$, and $Z_{4,3}$. Fig. 13 shows the actual and expected numbers of sensors deployed in the four zones. A problem is encountered that the actual number of sensors in zone $Z_{3,2}$ is $R_{3,2} = 3$ which is less than the expect number

$D_{3,2} = 4$. To avoid that $Z_{3,2}$ exhausts its sensors' power early, $\text{Left}(Z_{3,2}) = Z_{4,2}$ is checked if it has surplus sensor nodes that can help $Z_{3,2}$ reduce forwarding load. However, in zone $Z_{4,2}$, $R_{4,2} = D_{4,2}$. Therefore, the $\text{Right}(Z_{3,2})$ is further checked. Since zone $Z_{3,3}$ has been deployed with five sensor nodes and the expected number of sensors in that zone is two, we can use one sensor in zone $Z_{3,3}$ to transmit one data packet to zone $Z_{3,2}$ and augment the communication power of the other 4 sensor nodes in zone $Z_{3,3}$ to send a data packet to the $\text{Parent}(Z_{3,2}) = Z_{3,1}$ directly. Therefore the power consumptions of sensors in zones $Z_{3,2}$ and $Z_{3,3}$ are balanced. With the cooperation of Density-based and Distance-based Schemes, sensors in randomly deployed WSNs can balance their power consumption as much as possible and prolong the network lifetime.

5. Simulations

The section examines the performance of the proposed mechanisms. Our protocols were implemented using Glomomim [14]. The simulation discusses the Grid-based and randomly deployed WSNs. Two topologies are considered in the simulation, namely the proposed L-based Tree Topology and Random Tree Topology which is obtained by each node arbitrary selecting right or up node as its parent. In evaluating the performance of the proposed energy-balanced mechanisms, four energy-balanced schemes are compared, including the Distance-based Scheme, the Density-based Scheme, Hybrid scheme, and No-Control which does not involve any energy-balanced mechanism. Three MAC scheduling are used in the measurement, namely the Proposed MAC, the RTS/CTS MAC, and No control which does not involve any MAC scheduling. According to the L-based tree construction, the Distance-based, Density-based and Hybrid mechanisms are further applied to adjust the deployed position and the density of sensor nodes. In the simulation, performance of six approaches that combine different topology control schemes, energy-balanced schemes and MAC scheduling schemes are compared. The compared six approaches are de-

scribed in below. The *L-based_Distance_ourMAC* mechanism applies the proposed L-based scheme, Distance-based scheme, and the proposed MAC scheduling as the policies for tree construction, energy-balanced deployment, and MAC scheduling, respectively, whereas the *L-based_Density_ourMAC* mechanism applies the proposed L-based scheme, Density-based scheme, and the proposed MAC scheduling as the policies for tree construction, energy-balanced deployment, and MAC scheduling, respectively. The *Random_No_Demand* randomly constructs the tree but does not involve any energy-balanced or MAC scheduling mechanism. The *Random_No_RTS/CTS* MAC constructs a random tree and applies RTS/CTS MAC scheduling but does not involve any energy-balanced scheme. Finally, the *L-based_No_RTS/CTS* MAC and *L-based_No_Demand* applies L-based tree without involving any energy-balanced scheme. However, the former applies RTS/CTS MAC mechanism and the later send data packet on demand without involving any MAC scheduling.

We deploy sensors with different densities in the environment to compare the proposed three energy-balanced mechanisms. Table 1 lists the parameters used in the simulation.

The performance study of the proposed mechanisms is investigated in terms of (a) Average End-to-End Delay; (b) Network Lifetime; (c) Standard Deviation of Remaining Power; and (d) Accumulated Throughput.

5.1. Average end-to-end delay

Fig. 14 examines the performance of the compared six approaches in terms of end-to-end delay. In general, the end-to-end delay of five mechanisms increases with the number of sensors. Since the proposed L-based tree topology scheme establishes a balanced tree in the Topology Construction Phase and the proposed MAC scheduling avoids data collision, the *L-based_Distance_ourMAC* and *L-based_Density_ourMAC* approaches outperform the other four mechanisms in terms of the end-to-end delay. The performance results also reveal that applying MAC scheduling can efficiently reduce the delay time. As found in Fig. 14, the delay times of the *Random_No_RTS/CTS* MAC and *L-based_No_RTS/CTS* MAC are smaller than one of the *Random_No_Demand* and *L-based_No_Demand* approaches.

5.2. Network lifetime

Fig. 15 compares the performance of six approaches in terms of the network lifetime. In general, the energy con-

Table 1

Parameters used in the simulation

Number of Sensor: N^2-1	$N = 3-50$
Initial zone size	Distance-based: $40 \times 40 \text{ m}^2$ Density-based: $40/\sqrt{5} \times 40/\sqrt{5} \text{ m}^2$
Initial energy	5 W
Transmission power consumption	<21 mW
Receiving power consumption	14.4 mW
Transmission range	40 m
Path loss exponential	$\alpha = 2$
Packet size	20 Kbit
Time for transmitting a packet	1 unit
Collision delay	1.5 unit

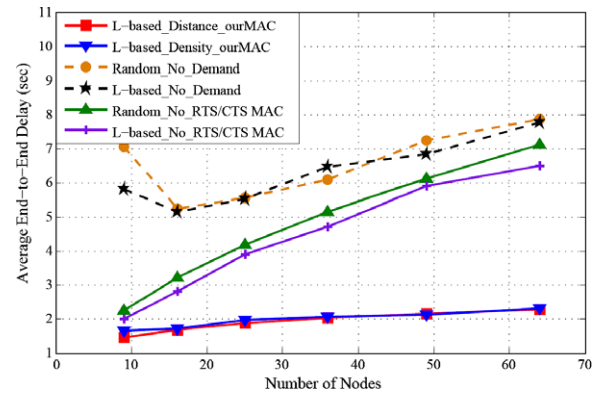


Fig. 14. Performance evaluation in terms of the Average End-to-End Delay.

sumption of the whole network increases with the number of sensor nodes owing to the increment in the number of forwarding packets. As shown in Fig. 15, the network lifetimes of the proposed Distance-based and Density-based mechanisms are longer than that of the other four approaches. When the number of sensor nodes is large enough, the Density-based scheme has a better performance than Distance-based scheme. The reason is that the Density-based scheme arranges more sensor nodes in sleep mode in each zone and conserves more energy.

Fig. 16 shows the performance comparison of the three proposed energy-balanced approaches with different deployment densities in a given randomly deployed WSN. The Density is measured by $\text{Density}(Z_{x,y})/\text{Density}(\text{Parent}(Z_{x,y}))$. The Hybrid approach resolves the problem that the actual number of sensor nodes in the zone $Z_{x,y}$ cannot meet the expected density. It uses superfluous sensor nodes from $\text{Left}(Z_{x,y})$ and $\text{Right}(Z_{x,y})$ to help $Z_{x,y}$ forward data packets to $\text{Parent}(Z_{x,y})$ by applying the power control mechanism and hence reduce the power consumption of $Z_{x,y}$. Therefore Hybrid approach results in a better performance than the other two approaches in terms of the network lifetime. The Distance-based approach per-

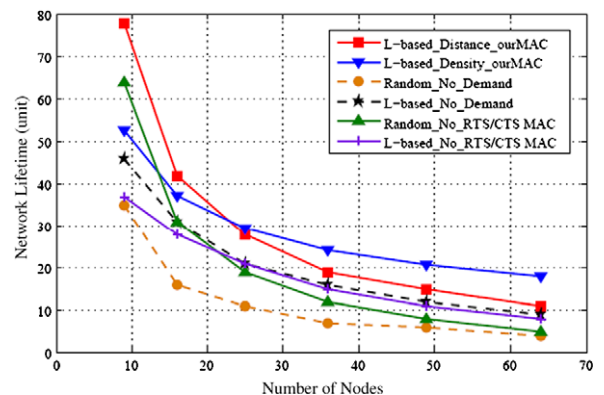


Fig. 15. Performance evaluation in terms of the Network Lifetime.

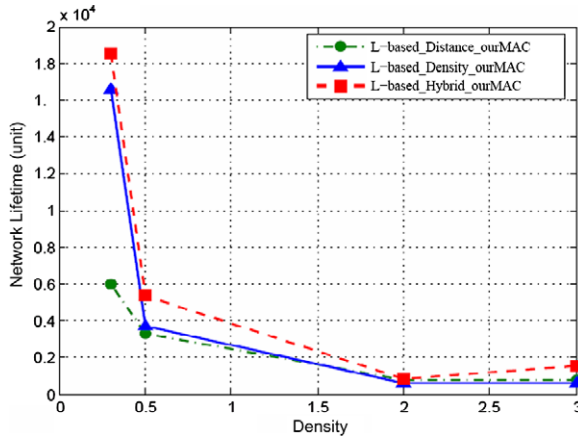


Fig. 16. Performance evaluation of the three proposed energy-balanced schemes.

forms worst in density 0.5 since fewer sensors were deployed in the area which is farthest away from sink node.

Fig. 17 shows the performance comparison of Hybrid scheme with different deployment densities in a given randomly deployed WSN. The Hybrid approach performs best in case that the Density is 1/3. It is because that the lifetime is mainly determined by the lifetime of those zones that are closer to the sink node. With this density, the zones closer to the sink node are deployed with more sensor nodes. In other words, the density of 1/3 results in fewer zones whose actual number of sensor nodes cannot meet the expected number. Therefore, the WSN with a density of 1/3 has the best performance in terms of the network lifetime.

5.3. Standard deviation of remainder energy

Fig. 18 compares the Standard Deviation of Remainder Energy of the six approaches. With the control of distance between sensor nodes and the transmitting power, the Distance-based approach balances the power consumption of each sensor in a WSN and therefore its Standard Deviation of Remainder Energy maintains at a fairly low value de-

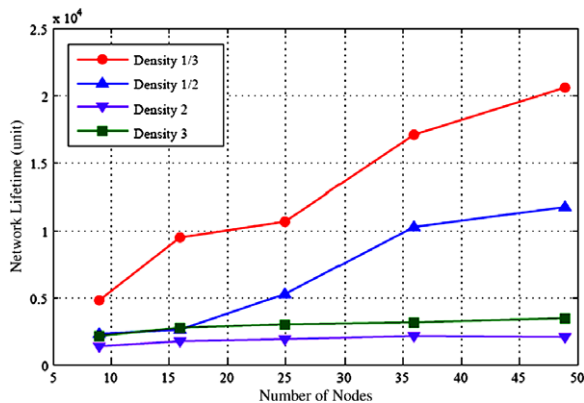


Fig. 17. Performance evaluation of Hybrid scheme with different deployment densities in terms of the Network Lifetime.

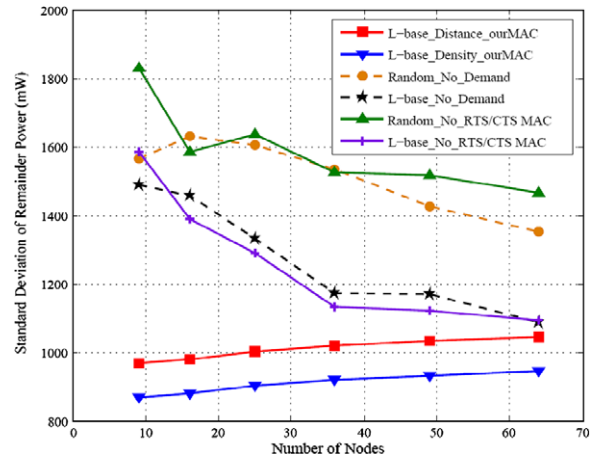


Fig. 18. Performance evaluation in terms of the Standard Deviation of Remainder Energy.

spite the number of sensor nodes increases. In addition, the Standard Deviation of Remainder Energy of the Density-based Scheme increases slowly with the number of sensor, indicating that the power consumption of each sensor can be balanced irrelevantly with the number of sensors. With the control of sensor density in each zone and sensor states in active/sleep modes, the Density-based approach significantly improves the power unbalanced consumptions and therefore outperforms the other four approaches in terms of the Standard Deviation of Remainder Energy. Note that even though Random Topology approach and L-based Topology approach involve MAC Scheduling, they still obtain poor performance in the Standard Deviation of Remainder Energy. This also reveals that the developed Distance-based and Density-based approaches significantly balance the power consumptions no matter the MAC protocol is involved or not.

Fig. 19 shows the performance results for the three proposed energy-balanced mechanisms in a randomly deployed WSN with different deployment densities. In general, all the three mechanisms have poor performance in density 1/3 and 3 because that the number of sensors in the zone, say Z_a , which is closest to the sink node diverges greatly from the zone, say Z_b , which is farthest to the sink node. In case that the Density of a given WSN is 1/3, most sensors in Z_b exhaust their energy early but sensors in Z_a only consume a little energy due to lots of sensors randomly deployed in the same zone. Fig. 19 depicts that the three proposed energy-balanced mechanisms work well in terms of Standard Deviation Remainder Energy when the Density value is between 0.5 and 2. It is interesting that Figs. 17 and 19 depict that a density of 1/3 is good for the network lifetime but bad for the Standard Deviation of Remainder Energy. A density of 1/3 only guarantees that the actual number of sensors is similar to the expected number of sensors deployed in the zones closer to the sink node. This helps to prolong the lifetime of those zones closer to the sink node. Since the lifetime of these zones mainly determines the lifetime of the WSN, a density of 1/3 is good for network lifetime. On

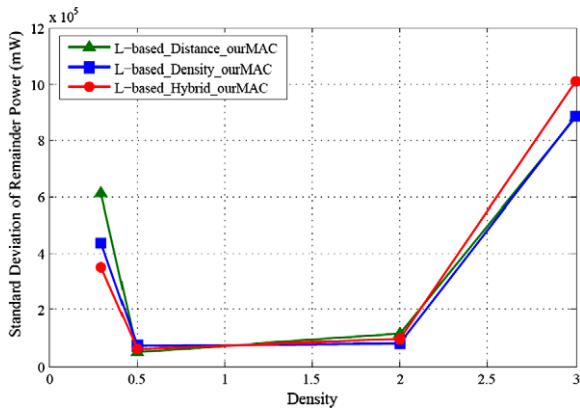


Fig. 19. Performance evaluation of the three proposed energy-balanced approaches with different deployment densities in terms of the Standard Deviation of Remainder Energy.

the other hand, a density of 1/3 makes a significant difference in the numbers of sensors deployed in Z_a and Z_b , and hence results in a significant value of Standard Deviation of Remainder Energy.

Fig. 20 shows the performance results of the Hybrid approach with different deployment densities. The Hybrid scheme has poor performance in densities 1/3 and 3 because the number of sensors in Z_a diverges greatly from that in Z_b . The reason is similar to that of Fig. 19.

5.4. Accumulated throughput

Fig. 21 compares the six approaches in terms of the accumulated throughput. In general, the accumulated throughput increases with the time in the first stage. However, since the sensor nodes closer to the sink node have more traffic, they will be failure earlier than the other nodes and thus cause network partition. As a result, the accumulated traffic maintains a constant value in the rest stage. The *Random_No_demand* and *Random_No_RTS_CTS* MAC mechanisms randomly construct the tree without considering the energy-balanced and load-balanced issues.

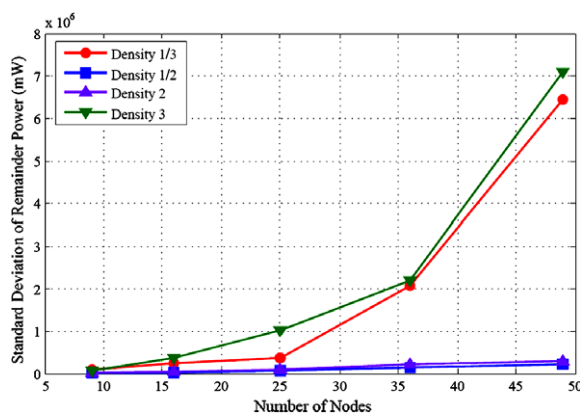


Fig. 20. Performance evaluation of Hybrid scheme with different deployment densities in terms of the Standard Deviation of Remainder Energy.

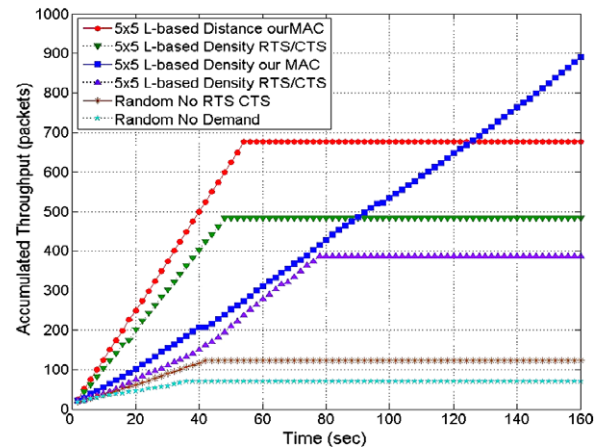


Fig. 21. Performance evaluation in terms of the accumulated throughput.

Therefore, these two mechanisms have poor performance in terms of the network life time and the accumulated traffic. The *Random_No_RTS_CTS* MAC method applies the RTS/CTS MAC to avoid packet collision and thus outperforms the *Random_No_demand* method in terms of the accumulated throughput. In general, the accumulated throughput of L-based tree topology is better than that of the random topology. Based on the constructed L-based tree, the proposed energy-balance mechanisms including the Distance-based and the density-based mechanisms adopt the RTS/CTS MAC mechanism and the proposed MAC scheduling mechanism. Applying the RTS/CTS scheme, sensor nodes within the transmission range of sender and receiver cannot transmit data packets simultaneously. The RTS/CTS MAC scheme may raise the expose terminal problem which reduces the degree of simultaneous transmissions. Furthermore, the contention between senders also reduces the throughput performance of RTS/CTS scheme. The MAC Scheduling scheme proposed in this paper takes the collision set into account and therefore exploits full opportunities for simultaneous transmissions. As a result, the proposed mechanism enhances the simultaneous transmission and improves the accumulated throughput. The Distance-based mechanism controls the sender's power appropriately and enables more senders transmitting data packets at the same time. Hence the Distance-based mechanism outperforms the Density-based mechanism in terms of the accumulated throughput.

Fig. 22 shows the throughput comparison of the three proposed energy-balanced approaches for a randomly deployed WSN with different deployment densities. In general, all three mechanisms have poor performance in density 3 because that there are few sensor nodes in zone Z_a and the number of sensors in Z_a diverges greatly from that of zone Z_b . Hence a lot of data packets generated in zone Z_b are required to be forwarded by sensors in zone Z_a , resulting zone Z_a to be the bottleneck for packet transmission. On the contrary, when the density is 1/3, Z_a has more sensor nodes to forward data packets. Hence all three mechanisms have a good performance in throughput. In comparison, the Hybrid mechanism has a better perfor-

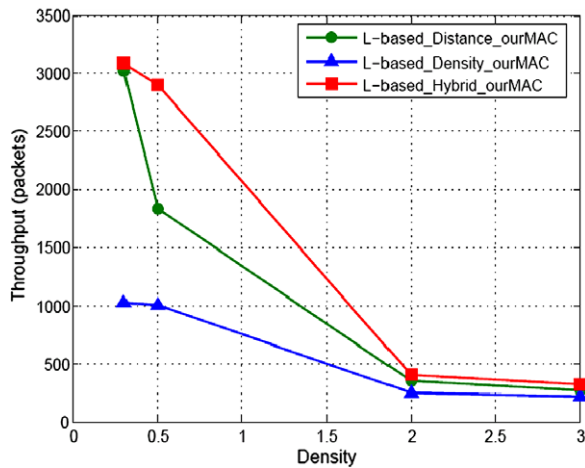


Fig. 22. Throughput evaluation of the three proposed energy-balanced approaches with different deployment densities.

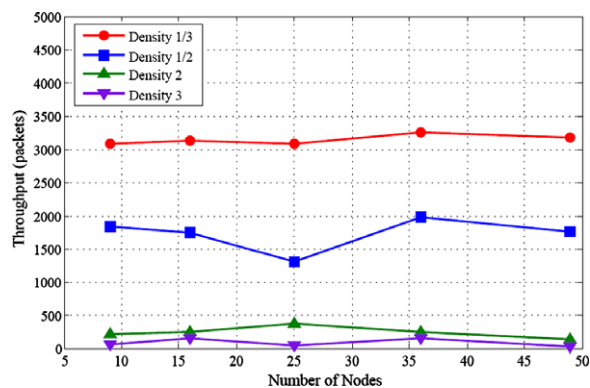


Fig. 23. Throughput evaluation of Hybrid scheme with different deployment densities.

mance in throughput since it takes full advantages from the other two mechanisms.

Fig. 23 examines the performance results of the Hybrid approach with different deployment densities. The Hybrid approach performs best in case that the Density is 1/3. It is because that the zones closer to the sink node are deployed with more sensor nodes, and hence these zones are likely not to be the bottleneck for packet transmissions. The proposed MAC scheduling exploits maximal opportunities for simultaneous transmissions and constrains those transmissions which may raise the packet collisions. Consequently, the four cases generally keep a constant throughput when the total number of sensor nodes is increased.

6. Conclusions

This paper firstly proposes an L-based Topology Construction mechanism then develops Distance-based and Density-based schemes for balancing power consumption of sensors in a Grid-based WSN. The Distance-based

Scheme adjusts the deployed position of sensor nodes and employs Power Control mechanism to balance the power consumption of sensor nodes. The Density-based scheme partitions the WSN into a number of equal-sized zones, adjusts the sensor nodes density in each zone and arranges sensor nodes in active mode in turn to balance the energy consumption of sensor nodes. In addition, based on the derivation of the possible collision set according to the distance between the sensor nodes, a collision-free MAC Scheduling protocol is proposed for sensors transmitting their sensing information to the sink node simultaneously. Based on the Distance-based and Density-based mechanisms, a Hybrid mechanism is proposed to extend the usage of the proposed protocols from a Grid-based WSN to a randomly deployed WSN, making randomly deployed sensor nodes able to reach the objective of power balance. Simulation results reveal that the developed Distance-based, Density-based, and Hybrid schemes involved in MAC Scheduling efficiently balances each sensor node's power consumption, avoids data collision, enhances simultaneous transmissions and prolong the network lifetime.

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