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Research Article

The PSL MAC Protocol for Accumulated Data Processing in the Energy-Harvesting Wireless Sensor Network

Ruihong Wang, Wuyungerile Li, Fei Gao, and Taofeng Jiao

Inner Mongolia University, China

Correspondence should be addressed to Wuyungerile Li; gerile@imu.edu.cn

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In the energy-harvesting wireless sensor network (EH-WSN), the actual energy-harvesting rate of each node varies due to the difference in node deployment or a sudden change in the environment. Therefore, when a node with a low energy-harvesting rate is used as a relay node, its energy is depleted at an accelerated rate. This reduces connectivity and network life, thus causing data accumulation on the node and the neighboring nodes. This study proposes a medium access control (MAC) protocol to avoid data accumulation in nodes; the proposed algorithm comprises the following: (1) a data transmission mechanism based on probability control for high channel utilization and (2) an accumulation data processing mechanism (power control, same layer transmission, and "layer-down" processing, PSL) to circumvent data accumulation. The simulation results show that PSL improves the network throughput and reduces the packet loss rate, while effectively solving the data accumulation problem.

1. Introduction

Wireless sensor networks (WSNs) have been developed rapidly and used widely owing to their characteristics such as no infrastructure requirement, low cost, small size, and ease of deployment. However, the limited battery power and single mode of power supply restrict their further development. Furthermore, replacing batteries is not an economic, safe, or environment-friendly approach, especially in harsh environments [1, 2]. For the aforementioned reasons, energy-harvesting WSNs (EH-WSNs) have gained popularity as a viable alternative. EH-WSNs are no longer limited to dry battery energy; they can accrue clean energy from the environment to power the nodes. EH-WSNs circumvent the shortcomings of traditional WSNs with regard to energy storage and supply. With proper control of the collected energy, EH-WSNs can work indefinitely [3, 4]. However, due to environmental and climatic variations, the rate of harvested energy at the nodes of EH-WSNs, which switch between the working and sleeping modes, is inconsistent [5].

Conventional studies on WSNs have focused on reducing power consumption, extending network lifetime and accomplishing a larger number of tasks with minimum energy consumption [6, 7]. However, energy-saving and network lifetime are no longer the primary focal points of studies pertaining to EH-WSNs.

In EH-WSNs, nodes are always deployed in outdoor environments, which are often harsh and uninhabited areas. In addition, solar irradiation varies widely with time, weather, and season and is greatly influenced by the placement angle of the solar collector. Therefore, in practical applications, solar energy collection is largely subjected to environment factors such as time, season, wind, sand, rain, snow, light blocking, and damage resulting from animals and plants. The aforementioned factors can potentially lead to insufficient node energy supply or intermittent energy supplements, thus resulting in unstable node energy. Consequently, the stability and reliability of network connectivity are affected, which results in the formation of isolated nodes that can accumulate a large amount of historical data. To address the aforementioned roadblocks, we propose a stacked data processing algorithm in a harsh environment. To avoid data conflict, a data transmission mechanism based on probability control is proposed. In addition, after the data accumulation occurs in the node, the method of increasing power, same layer forwarding, and "layer-down" processing is considered to deal with the problem of data accumulation.

The rest of this paper is organized as follows: In Section 2, the existing medium access control (MAC) protocols for EH-WSNs are introduced, along with some power control algorithms and the characteristics of environmental energy. Section 3 proposes the probabilistic transmission mechanism to avoid signal conflict and proposes an accumulation data processing mechanism to solve the accumulation data problem, while the simulation results are presented in Section 4. A summary of the study and its achievements is presented in Section 5.

2. Related Work

Extensive studies and the widespread utilization of new clean energy sources have led to the advancement of the environmental energy collection technology, with steady improvements in energy collection efficiency. Kansal [8], Park Chou [9], Zhu [10], and other scholars have established mathematical models to demonstrate the collection of environmental energy for WSNs. In 2005, Raghunathan proposed the concept of EH-WSNs [11], with the idea of collecting energy from the environment for sensor nodes by using the traditional MicaZ wireless sensor node. Kansal [11] set up a model for energy collection, which optimized the work cycle and task scheduling of the nodes [12], as well as the energy utilization and service life of the whole system [8]. AH-MAC (adaptive hierarchical MAC protocol) [13] is an adaptive MAC protocol initiated by the sink node. It optimizes the duty cycle to prolong the sleep mode of the network, thereby reducing the energy consumption and improving the throughput.

On-demand MAC protocol (ODMAC) [14] can be customized according to the requirements of specific applications. The protocol supports nodes with different duty cycles, which enables each node to maintain its energy consumption at the same level as the energy collected, and each node can operate as close to energy neutral operation as possible. The ID polling MAC protocol [15] is initiated by the sink node and polled by the node number (ID). In EH-WSNs, energy collection and conversion of a node are often affected by time, space, climate, and other factors. Moreover, static transmission power, transmission range, link quality, and topology control have no significant effect in optimizing the energy collection network in harsh environments. Therefore, real-time transmission power control is proposed in EH-WSNs. Xu et al. proposed a dynamically adjusted duty cycle-optimized congestion scheme based on real-time queue length (ADCOC) [16], which avoids network congestion, minimizes system latency, and improves energy efficiency. Tang conducted research to analyze blind spot localization in road traffic WSNs [17] and proposed solutions and measures to reduce monitoring results. In QAEE-MAC [18], the receiver node selects the sender node according to the sender's data priority, and the receiver node also adjusts its wake-up period based on the energy state. Therefore, the energy consumption of the receiving node can be minimized.

3. Accumulated Data Processing Algorithm in the Energy-Harvesting Wireless Sensor Network

In EH-WSNs, the actual energy-harvesting rate of each node in the network is different due to differences in the deployment environments of the nodes or the sudden change in the environment around the nodes. Therefore, when a node with a low energy-harvesting rate is used as a relay node, its energy will be depleted at an accelerated rate. This eventually decreases the network's connectivity and network life. Simultaneously, data accumulation occurs on the node and the neighboring nodes. Failure to handle the accumulated data accurately will cause a high packet loss rate in the network, thereby reducing network throughput. This paper proposes a MAC protocol to deal with the problem of data accumulation; the protocol comprises two proposals: (1) a probabilistic transmission mechanism to solve the problem of signal conflict that may occur between the sender and the receiver and (2) an accumulation data processing mechanism of "power control," "same layer forwarding," and "layer-down processing" (PSL) to address the data accumulation problem caused by differences in the energy-harvesting rate of nodes.

3.1. Network Model. This paper adopts a hierarchical convergent data harvesting model, where a flat structure is centered on a sink node, and sensor nodes in the network carry solar panels to power themselves. The sink node collects and processes the perception data of all the nodes in the network. Except for the outermost node, all other nodes can be used as relay nodes. The outermost node only senses data and does not perform data-forwarding tasks. The sink node is assumed to have a continuous power supply, as the sensor nodes use solar modules to harvest environmental energy to perform sensing and relay tasks. The hierarchical convergence EH-WSN topology is shown in Figure 1.

As shown in Figure 1, the outer node sends the perceived data to the inner node, whereas the inner node merges the data received from the outer node with the data it senses and sends them to the next-hop neighboring node. In this manner, data are transmitted to the sink node. In the existing EH-WSN, due to the characteristics of the node itself and the characteristics of environmental energy, the sensor node cannot work continually. A sensor node has the following two states:

(1) Sleeping state: In this state, the wireless transceiver and the microprocessor stop working, thus reducing energy consumption to a minimum

(2) Working state: The node is in a working state after being fully charged. The working state can be further divided into the random back-off state, carrier monitoring state, data sending state, and data receiving state

There are two types of sending states: (1) sending a data request packet and (2) sending the data that the node perceives or receives from an outer node.

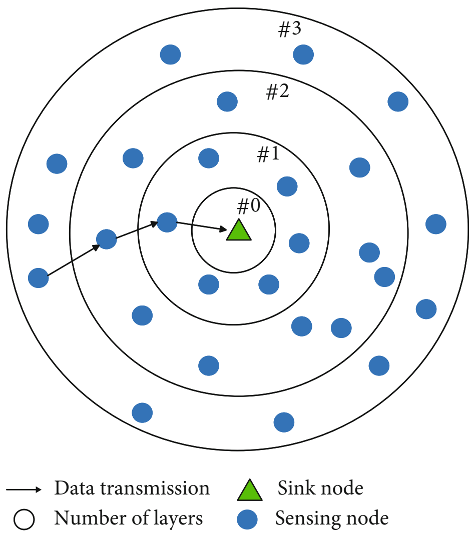

FIGURE 1: Network topology.

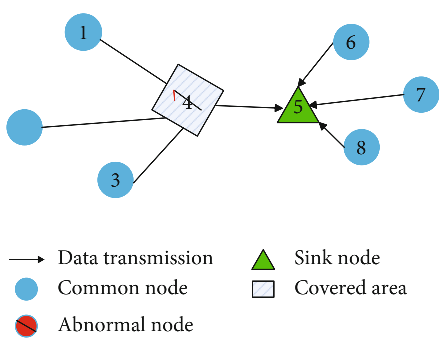

FIGURE 2: Data accumulation due to insufficient energy in the relay node.

Similarly, the receiving state is divided into two types: (1) waiting for the request response packet and (2) waiting for the data packet sent by the outer node.

3.2. Cause and Solution to the Regional Data Accumulation Problem. Solar panels are the most widely used energy-harvesting equipment; however, the energy-harvesting rate of solar panels is greatly affected by factors such as time, weather conditions, and node locations. When the solar panel is inclined or covered, it has a significant impact on the rate of energy harvesting. The energy-harvesting rate of a single sensor node may affect the network performance of the entire EH-WSN to a certain extent, especially when these are relay nodes. This is because it will affect the connectivity of the network and cause data accumulation problems on some nodes. Figure 2 illustrates the situation when the relay node has insufficient energy.

The figure shows five nodes in a given network. Nodes 1, 2, and 3 are common sensing nodes; node 4 has both sensing and forwarding functions; and node 5 is the sink node. In general, the energy-harvesting efficiency of all nodes in similar locations should be at a similar level. However, node 4 cannot continue to harvest energy due to being covered, thus causing node 4 to become an abnormal node. Consequently, nodes 1, 2, and 3 that forward data through node 4 will become isolated nodes in the network and cannot transmit data, leading to data accumulation.

3.3. Probability Control Data Transmission Mechanism. Regardless of the type of harvesting equipment employed for EH-WSNs, the energy-harvesting rate of each node is not the same, which renders it impossible for EH-WSNs to set all scheduling information during initialization. Therefore, this study proposes a data transmission mechanism based on the probability control including collision avoidance and data probability transmission.

(1) Collision avoidance: In wireless communication, a sending node sends data packets to a receiving node. The data transmission process will not commence if the transmission channel is busy. Hence, a channel allocation mechanism suited to our defined network model is needed. It was designed as follows: When a node in the network is activated from the sleep mode, the node will randomly select a back-off value in the random back-off window as the random back-off time. Thereafter, the node detects the channel within the random back-off time and assumes a receiving state after securing the channel. When the node receives data from an inner node, it immediately shifts from the receiving state to the sending state and transmits the received data. After sending the data, the node switches to the carrier monitoring state until the channel is idle and then initiates a new receiving state, where the aforementioned process is repeated

(2) Data probability transmission: This study proposes a MAC protocol initiated by a receiving node. Data conflicts occur at the receiving node when a receiving node receives data simultaneously from two or more sending nodes. This study attempts to solve this issue through sending data probability. The process is outlined as follows: After the sending node responds to the data request packet from the receiving node, it waits for the response packet from the receiving node. The response packet of the receiving node includes a value n, which is received by the receiving node within the waiting time after sending the data request packet. The response packet of the receiving node includes a value n, where n is the total number of request response packets received by the receiving node within the waiting time after sending the data request packet. After receiving the value, the sending node takes the reciprocal n, generates a random number p between 0 and 1, and compares p with 1/n. When p is >1/n, the energy state is assessed. If the energy is sufficient, the random back-off time is reselected to continue the predefined transmission process. Otherwise, it returns to the sleep state for charging operation. If the node

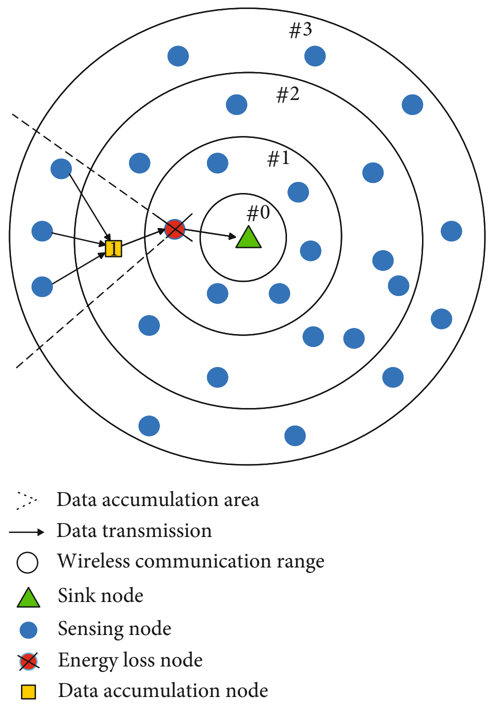

Figure 3: The case of data accumulation.

receives a data packet within the random back-off time, it stops receiving the data packet and switches to the carrier monitoring state until the end of the packet. When the channel is idle again and is still in the random back-off time, the node returns to the receiving state and repeats the appeal process until the end of the random back-off time or until a data request packet is received from the inner node

3.4. PSL-Stacked Data Processing Mechanism. The sensor nodes are deployed in the simulation area by using methods such as spreading. In EH-WSN, when the solar panel of a node is tilted, the energy-harvesting rate of the node cannot reach the average level of the network energy-harvesting rate. At this time, all nodes that use only this node as the relay node cannot transmit data to the sink node, resulting in regional data accumulation. The phenomenon of regional data accumulation is presented in Figure 3.

As shown in Figure 3, when a node has an energy loss phenomenon, the data of all nodes in the data accumulation area cannot be transmitted to the sink node, which may lead to data loss in some areas. The data in the entire accumulating area accumulate at accumulating node 1. When the buffer area of node 1 is full, it can neither sense new data nor receive data from other nodes; consequently, nodes in the data accumulating area inevitably become invalid nodes. Thus, data accumulation caused by the energy-harvesting problem of a single node decreases the performance of the entire network. This phenomenon has the least impact when it occurs at edge nodes, and it has the most considerable impact at relay nodes, especially at nodes around the sink node.

After a node wakes up, it sends the data buffered by the node. If a node does not receive the data request packet in threshold T_t, it is judged that data accumulation has occurred. This paper comprehensively considers that the threshold value used by all nodes is set as three times the average number of awakenings of nodes N_w, that is, $\mathrm{T_t} = 3 \times 2\mathrm{N_w}$ is considered the threshold for data accumulation judgment; the value of $\mathrm{N_w}$ verified by experiments as 6. Therefore, the processing mechanism for the data accumulation problem is as follows.

3.4.1. Increase Power

(1) When a node exceeds the preset number of wake-up times and fails to find a next-hop node, it increases the transmission power to send the emergency data beacon frame, and the data of the node are merged

(2) The node that receives the urgent data beacon sends a suppression packet. When other nodes in the network receive the suppression packet, they stop data transmission and enter a random back-off state to wait for the next data transmission or enter a sleep state to harvest energy

(3) After receiving the suppression packet, the node where data accumulation occurs increases the power of the fused data and transmits them. After the data transmission is complete, the node reduces the transmission power and restores to the original power value

(4) Then, the accumulation of the number of times is restarted, that is, the aforementioned process is repeated until the threshold number of times is exceeded again

(5) When the channel is idle, other suppressed nodes restart the normal data transmission process

When the transmission power of a certain node in a network is too large, multiple nodes receive the emergency data beacon frame simultaneously; these nodes also receive the emergency data packet at the same time. Although this process ensures the success of emergency data transmission, the priority protocols of emergency data packets may inhibit the sending of valid data packets to some extent, leading to wastage of resources. In this study, the following methods are used to control transmission power.

Let us assume that the initial communication radius of node S is $\mathrm{R_0}$, the network area is $\mathrm{C_r} \times \mathrm{C_r}$, and the number of nodes is N. When the connectivity of node S is 0, the following mechanism is used to ensure that node S finds and communicates with only the next-hop node as far as possible:

(1) Accumulation of the average number of wake-up times N_w for the node to find the next-hop node

(2) Calculation of the size Sn of the average area occupied by the node using the following:

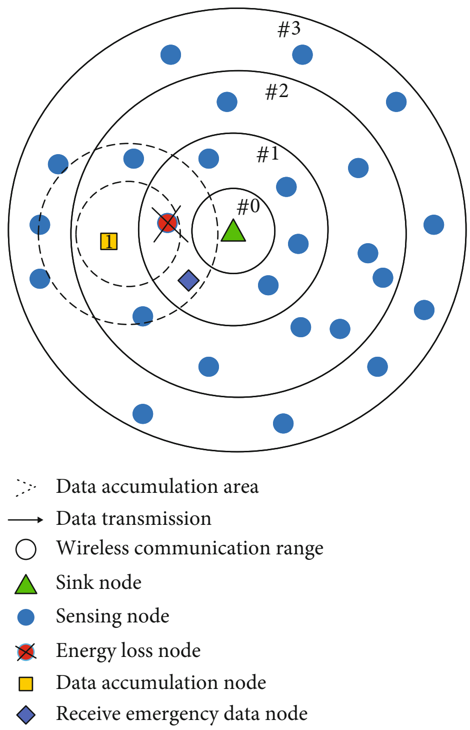

FIGURE 4: The case of increase power.

$$S_n = \frac{C_r \times C_r}{N}. \quad (1)$$

(3) Calculation of the radius R_i of the area where the power area needs to be increased. In this study, the number of times a node increases its power is equal to the average number of wake-up times Nw of the node, and this number is equally distributed to all radius $<1.5R_0$. The calculation is performed:

$$R_i = \sqrt{\frac{\pi \times R_0^2 + 2i \times S_n}{N}}, \quad (2)$$

(4) When the wake-up times of the node exceeds $2N_w$, the radius R_i of each increased power area is calculated using Formula (2)

(5) When $R_i > 1.5R_0$, the data are transmitted to the same layer node instead of increasing power, and from there, the data are sent to the sink node by a node in the same layer

Figure 4 shows a schematic of the power increase process. The data accumulation node increases the power, that is, it increases the wireless communication range; consequently, all nodes within the wireless communication range of the node receive the accumulated emergency data.

3.4.2. Same Layer Forwarding. Although EH-WSN relaxes the restriction on node transmission power to some extent, the following effects may occur when the power is excessively large:

(1) Effect on the normal transmission process of nodes within a certain range

(2) Excess consumption of the energy of the node, which increases the time required by the node to wake-up next time

(3) Broadcast storm: When the transmission power of the node is increased according to method 1 and the next-hop node is still not found, the wireless communication range of the node does not increase. Rather, the data are sent to another node in the same layer, and then, the same layer node sends the emergency data packet to the sink node. Herein, a hierarchical aggregation model is used to send emergency data to nodes at the same layer, ensuring success of the emergency data reaching the aggregation node. The same layer forwarding diagram is presented in Figure 5

As shown in the figure, node 1 becomes a data accumulation node because it cannot find the next-hop node. When the node cannot find its next-hop node after power is increased, it sends the data packet to nodes 1 and 2 in the same layer, bypassing the dead node, and then, again, the same layer node is used to send the accumulated data to the sink node.

3.4.3. "Layer-Down" Processing. Herein, a hierarchical aggregation model is used, in which a node sends its sensing data and the data received from an outer node to its inner node. When a node has accumulated data, it will "layer-down" and no longer request data from outer nodes. Instead, it participates in the data request processes of its peer nodes and outer nodes; the priority of data request packets of peer nodes is higher than that of outer nodes. "Layer-down" is advantageous as it can avoid further accumulation of data. The node maintains the "layer-down" state until it receives a data request packet from the inner node again; then, it judges whether to exit the "layer-down" state and then restarts the normal data transmission process. The node continues to accumulate the number of wake-ups that have not received a data request packet in the "layer-down" state and uses increased power and the same layer forwarding method for data transmission. The "layer-down" processing algorithm is presented in Figure 6.

As shown in Figure 6, when the energy-deficient node dies, node 1 judges itself to become a data accumulation node. It begins to participate in the data request phase of nodes 1 and 2 and the outer node 3 of the same layer. It may send the data of this node to the same layer node, or the outer layer may use the same layer and outer layer nodes to detour data to the sink node. The flow chart of PSL accumulation data processing mechanism is shown in Figure 7. When the node exceeds the threshold and cannot find the

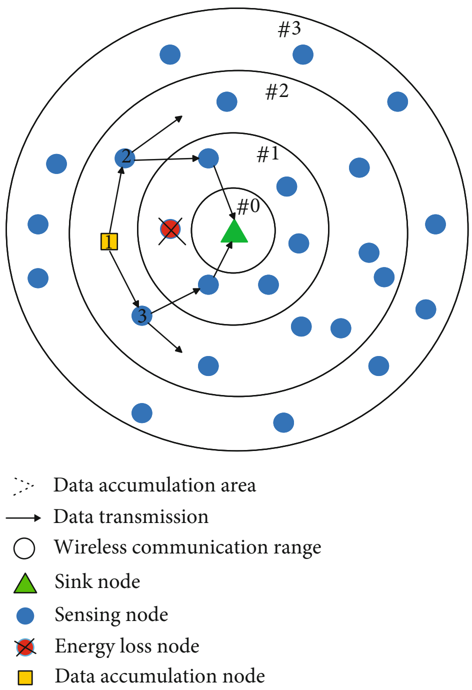

FIGURE 5: The case of peer forwarding.

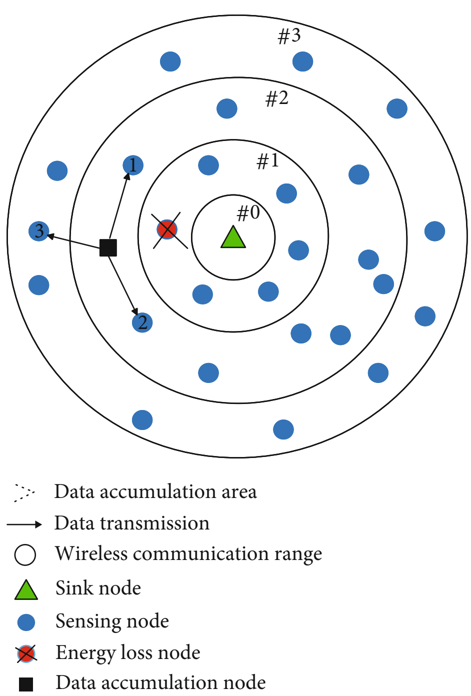

FIGURE 6: The case of “layer-down” processing.

next-hop node, the transmission power to send data is increased. If the node increases the power and fails to find the next-hop node, it will send the accumulation data packet to the peer node of the data accumulation node. If the data cannot be forwarded by the same layer forwarding, the data of the node is sent to the sink node by means of “layer-down” processing.

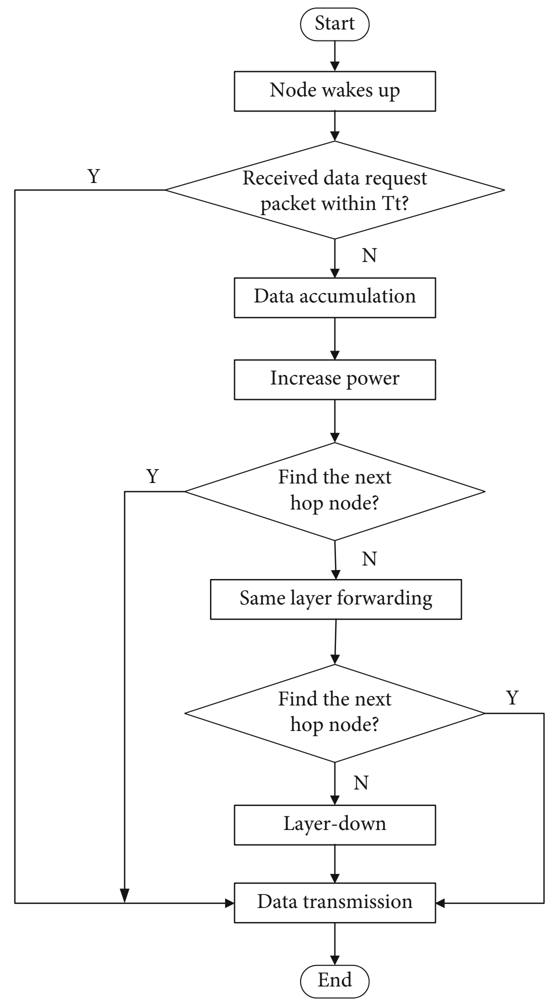

FIGURE 7: PSL accumulation data processing flow chart.

4. Simulation Results

4.1. Simulation Parameter Setting. In this study, MATLAB is used for simulations. The environment settings for simulation are as follows:

(1) In total, 10–100 energy-harvesting sensor nodes are randomly deployed in a simulation area of $300 \times 300\ m^2$

(2) Size of the data packet (S_d) is 100 bytes, whereas that for each for the data request beacon frame, request response packet, data transmission beacon frame, and emergency data beacon frame is 15 bytes

(3) The average transmission range of sensor nodes is 70 m

(4) The transmission rate of each sensor node is 250 Kbps

(5) The average energy-harvesting rate is 1–10 mW

(6) Receiving power and transmitting power of the node are 72.6 mW and 83.7 mW, respectively

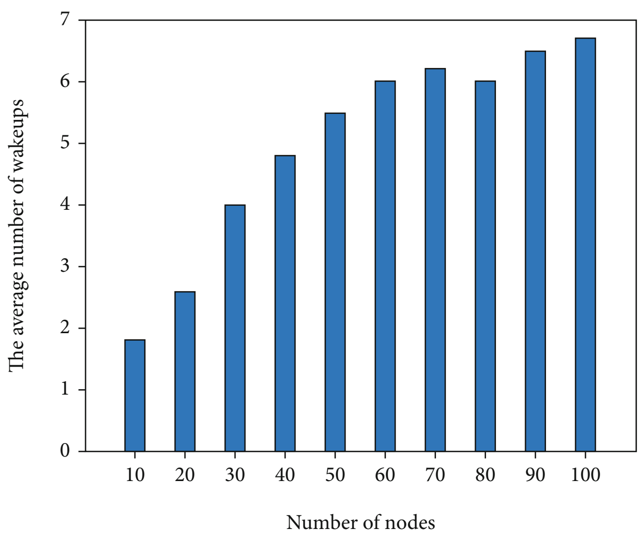

Figure 8: The relationship between the number of nodes and the average number of wake-ups.

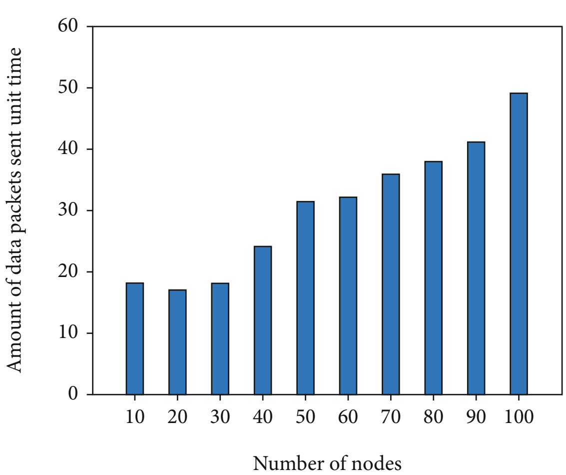

Figure 9: The number of accumulated data packets sent per unit time.

4.2. Analysis of Simulation Results. Figure 8 shows the relationship between the number of nodes and the average wake-up times of the identified next-hop node. When the number of nodes is only 10 and 20, the number of wake-ups for identifying the next-hop node for data transmission is twice on average. This is because the number of nodes in the lower network is small, and the probability that the channel remains idle is high. With an increase in the number of nodes, the number of times the node finds the next-hop node increases. This is because as the number of nodes increases, the number of signal collisions increases, and the probability that the channel remains idle after the random back-off time of the node decreases. As a result, the node will turn to a sleep state or reselect a random back-off time, because of which the average number of wake-up times for identifying the next-hop node increases with the increasing number of nodes.

The blue histogram in Figure 9 shows the relationship between the number of nodes and the number of data accumulation packets transmitted per unit time. With an increase in the number of nodes in the network, the number of data accumulation packets transmitted per unit time increases. When the number of nodes is small, there are more isolated nodes in the network. At this time, most of the data accumulation packets are generated and sent by the isolated nodes. Because the number of nodes is small, the isolated nodes can determine the next step through the PSL accumulation data processing mechanism. The probability of node hopping is also small. As the number of nodes increases, the number and frequency of isolated nodes to be accessed for identifying the next-hop node increase, and the number of data accumulation packets increases.

The network throughput when the number of nodes changes is shown in Figure 10. When the number of nodes in ID polling is <50, the network throughput increases with an increase in node density. When the number of nodes in the network reaches 50, the network throughput remains nearly unchanged. The throughput of ID polling is the lowest compared with the probabilistic polling and the MAC protocol proposed in this paper. The sink node selects only one node to communicate with at one time. The condition for successful data transmission is that the receiving node is in the wake-up state and receives only the beacon frame of this node ID number. Energy-harvesting nodes periodically harvest energy from the environment; however, the energy-harvesting process is longer than the communication process. Therefore, the probability that the node is in the receiving state with sufficient energy and receives only the beacon frame with its own ID is very small. Probabilistic polling has a higher throughput than ID polling because it uses competitive probability values instead of node ID numbers to select the communication node, avoiding having to select a fixed node as the only communication node each time, which increases the success rate of data transmission and further increases the network throughput. The proposed MAC protocol, thus, has higher throughput, as herein a node acts as the receiving node to transmit a data request packet after waking up, and it informs each transmitting node of the number of received response packets. The actual value replaces the probabilistic value, decreasing the time of collision and facilitating convergence of the probability values.

The packet loss rate with changes in the number of nodes is shown in Figure 11. ID polling only selects a certain node to communicate with each time, and no signal collision or collision occurs. The packet loss rate is independent of the number of nodes and remains zero. The packet loss rate of both probabilistic polling and the MAC protocol proposed in this study increases with an increase in the number of nodes. Probabilistic polling has a low packet loss rate before 50 nodes. QAEE-MAC always sends high-priority packets first, causing low-priority packets to fail. For a higher number of nodes, the proposed MAC protocol has better performance because in this case, actual values are used to increase the success rate of data transmission.

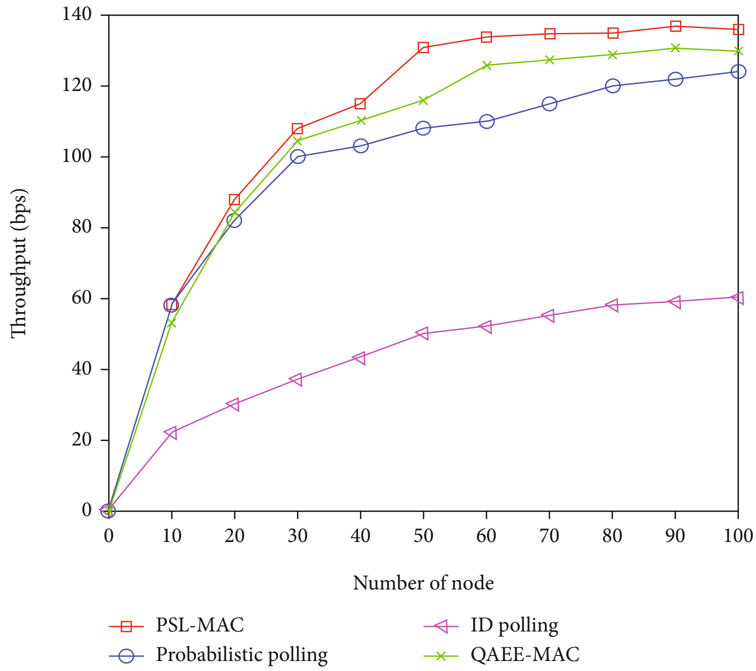

FIGURE 10: Network throughput when the number of nodes changes.

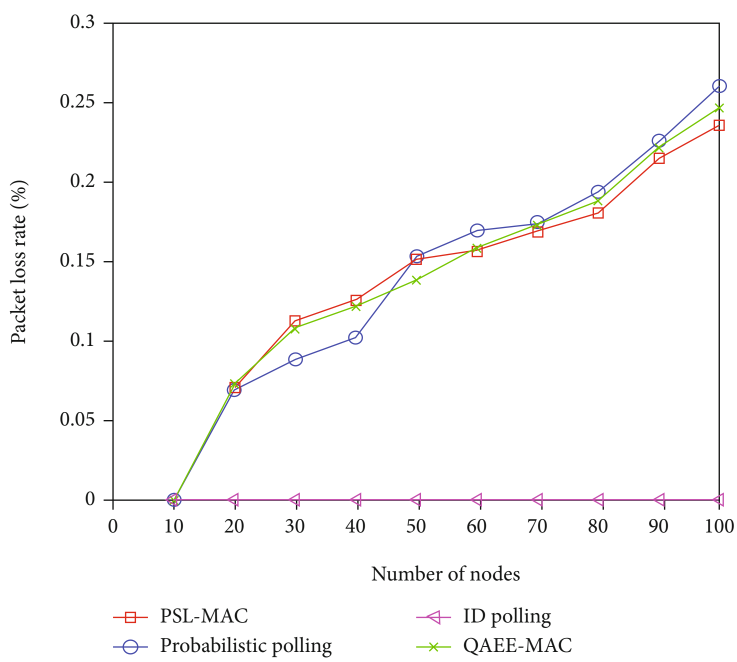

FIGURE 11: Packet loss rate when the number of nodes changes.

The throughput when the node energy-harvesting rate changes is shown in Figure 12. The network throughput of all the aforementioned three protocols increases with an increase in the energy-harvesting rate. The proposed MAC protocol has higher throughput. For ID polling, when the energy-harvesting rate increases, the node charging process is shortened, the probability of the node receiving the polling packet with the node ID is increased, and the throughput is also increased. With an increase in the energy-harvesting rate, the number of nodes in the wake-up state at the same time increases, and the probability value of probabilistic polling remains low, avoiding collisions and ensuring success of data transmission. QAEE-MAC uses priority to adjust the contention window size of the receiver, which reduces the throughput. For the proposed MAC protocol, when the energy-harvesting rate increases, the number of communicable nodes increases, and the network throughput increases accordingly. When the energy-harvesting rate

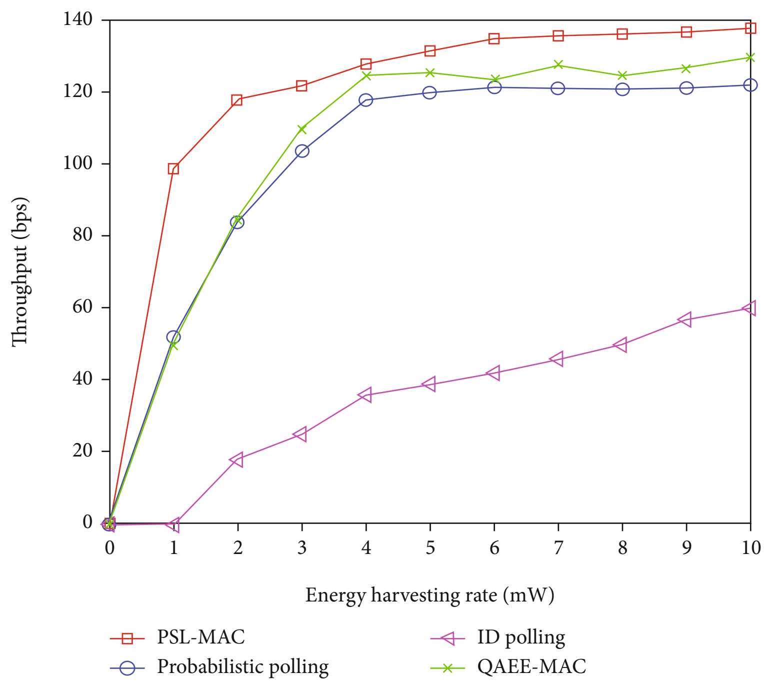

Figure 12: Throughput when the energy-harvesting rate changes.

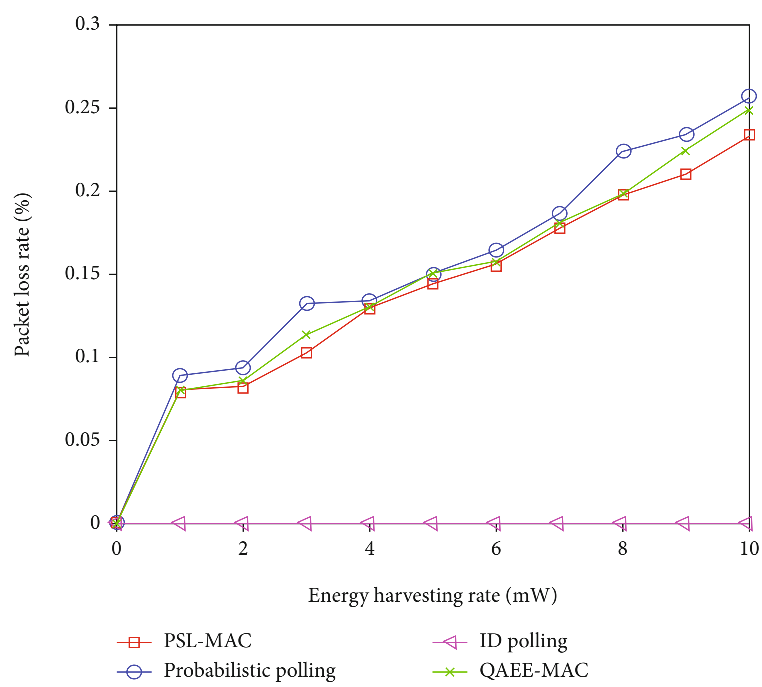

Figure 13: Packet loss rate when the energy-harvesting rate changes.

reaches a certain level, the throughput is not greatly affected by the energy-harvesting rate. This is because in this case, the sink node only establishes a connection with a certain node each time it wakes up, and more nodes return to the charging state to avoid collisions or reselect random back-off values to participate in the next competition.

The packet loss rate with changes in the node energy-harvesting rate is shown in Figure 13. ID polling only selects a certain node to communicate with it each time, thereby avoiding data collision, and thus, the packet loss rate remains zero. The probabilistic polling, QAEE-MAC, and the proposed MAC protocol packet loss rate in this study increase because of an increase in the energy-harvesting rate, which in turn increases the number of nodes in the wake-up state, the probability of channel competition and collision, and the packet loss rate. However, the proposed MAC protocol has a lower packet loss rate. This is because probabilistic polling uses the AIMD method to calculate the probability of competition for conflict avoidance, QAEE-MAC always sends high-priority packets first, causing low-priority packets to be in a dormant waiting state, and this paper uses the actual value of neighboring nodes when the node wakes up as the probability of competition to avoid conflict, resulting in a low packet loss rate.

5. Conclusions

This study proposes a MAC protocol called PSL for limited energy-harvesting conditions to solve the data accumulation problem in EH-WSNs. A data transmission mechanism based on probability control is also proposed to reduce data conflicts during data transmission. Simulation results show that the proposed PSL scheme can solve the problem of data accumulation and improve the network transmission rate.

Data Availability

All sensor nodes can collect data from the environment and forward the data they have collected.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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