IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 12, 2018, accepted November 13, 2018, date of publication November 22, 2018,
date of current version December 27, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2882918

Duty Cycle Adaptive Adjustment Based Device to Device (D2D) Communication Scheme for WSNs

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This work was supported in part by the National Natural Science Foundation of China under Grant 61772554, and in part by the Open Research Project of the State Key Laboratory of Industrial Control Technology, Zhejiang University, China, under Grant ICT1800391.

ABSTRACT Device to device (D2D) communication is a key candidate for 5G. Its purpose is to enable direct communication between user devices that are close to each other, thereby reducing the load on the base station. Wireless sensor networks (WSNs) have received a lot of attention as the basis for D2D. The opportunistic routing (OR) scheme is proposed to deal with data transmission problems in loss WSNs. In this paper, a duty cycle adaptive adjustment-based bopportunistic routing (DCAAOR) scheme is proposed to speed up reliable data transmission. According to the wake-up rule of nodes, we propose three different DCAAOR schemes, respectively. In modified opportunistic routing (MOR) scheme, the nodes are random awake/sleep. In active slot uniform distribution (ASUD) scheme, the active slot of relay nodes are evenly distributed by adaptive adjustment and the active slot group (ASG) scheme divides the active slots of the relay nodes into groups. The active slots of each group are the same, and the active slots of different groups are evenly distributed. After a lot of theoretical analysis, the ASUD and ASG scheme proposed in this paper is superior to the simple modified MOR scheme in terms of energy consumption and delay. When the duty length $\tau = 20$, the energy consumption of the nodes in the MOR scheme is reduced by 38.75% compared with the OR scheme, and the other two schemes are reduced by 41.83%.

INDEX TERMS Device to device, opportunistic routing, duty cycle adaptive adjustment, delay, lifetime.

I. INTRODUCTION

With the advancement of technology, the Fourth Generation (4G) cellular networks has been developed to represent wireless broadband systems such as mobile data, mobile computing and mobile multimedia [1]–[4]. With the rapid spread of smart terminals and the explosive growth of information, wireless communication technologies for 5G is emerging. Device to Device (D2D) communication has received wide attention as a key candidate for 5G [3]–[5]. The Internet of Things (IoT) is the foundation of D2D communications and is an important cornerstone that must not be ignored [5]–[8].

The IoT is the latest Internet evolution that incorporates billions of Internet-connected devices that range from cameras, sensors, RFIDs, smart phones, and wearables, to smart meters, vehicles, medication pills, signs and industrial machines [9]–[13]. Collecting and integrating data, and distilling the high value information through a large amount of IoT devices, the IoT and related technologies have the promise of realizing pervasive and smart applications, which, in turn, have the potential of improving the quality of Life of people living in a connected world [14]–[17]. Sensor based devices are an important component of IOTs [18]–[21]. It is estimated that the number of devices equipped with various sensing devices connected to IoTs has exceeded the number of humans, and is expected to reach 9 billion by 2020 [22].

Wireless Sensor Networks (WSNs) are the most concentrated networks of sensor nodes and are an important component of IoT [23]–[27]. Wireless sensor nodes are an important component of WSNs that collect, process, and forward data and send packets to the control end (sink) [28]–[31]. Sink receives the data packets sent by the sensor node, controls the changes in the network in real time, and makes corresponding feedback in time [32]–[35]. WSNs are especially suitable for special environments, such as enemy surveillance, active volcano monitoring, wildlife protection, etc. With the development of microprocessor technology, the calculation and processing capabilities of sensor nodes have been very powerful. Combined with big data technology and artificial intelligence technology, WSNs are easier to deploy, and the advantages of self-organizing networks can be further developed [35]–[37]. This has caused widespread concern in industry and academia.

The most important feature of wireless sensor nodes is the limited energy, so energy efficiency is a very important research content [36]. At the same time, reliable and timely data transmission has always been an important research content in WSNs [3], [8], [15], [26].

(1) The effectiveness of energy [3], [8], [15], [26]. To facilitate deployment and reduce economic costs, wireless sensor nodes are typically powered by batteries. The battery is generally small and has limited capacity. Sensor nodes are generally deployed in dangerous, hard-to-reach places, so it is unrealistic to replace or recharge the drained sensor. Therefore, how to save the energy of the sensor network and maximize the lifetime of the network is one of the important research issues. Related scholars have proposed a variety of ways to save energy of sensor nodes. Among them, the most common method is the duty cycle control [14]. That is, let the sensor node periodically awake/sleep. When the node is in sleep state, the energy consumed is less than 1% of the energy consumption in the awake state, so increasing the duty cycle control can save energy.

When the node adopts the duty cycle control, the node selects one slot to wake up, and sleeps in other $\tau - 1$ slots, which greatly reduces its energy consumption. In most WSNs, especially those with sparse data generation, the data generated by the nodes is sparse, and most of the time nodes are idle. For example, in the monitoring of forest fires, wildlife and crop environments, and even in the monitoring of important parts of the bank (data only occurs in the event of an abnormality), the node sometimes generates a packet within a day or even days. Therefore, it is better to use the duty cycle based mode in such networks. This ensures that the network has a long lifetime, and other performance can meet the needs of the application.

(2) Low Delay. Delay is another problem worth studying in WSNs. Delay mainly refers to the end-to-end delay, which is defined as the total time it takes for the data packet to be transmitted from the source node to the sink after multi-hop routing [10], [14], [26]. End-to-end delay consists of the delay of each hop route. The one-hop route delay is defined as the time that the data packet is received by node A and sent to the next node.

In the process of one-hop transmission [6], [18], [36], the delay of the node is mainly generated by the following operations. These operations include: taking the packets out of the receive buffer, performing certain computations on the packets (such as data fusion, data encoding, etc.), putting the packets into the buffer, waiting in line, and transmitting. WSNs generally generate less data. Therefore, in the case that the wireless channel is not good, the delay mainly comes from the data transmission mode. Especially for the network with high packet loss ratio, the packet needs multiple retransmissions and thus causes a large delay. In summary, the data transmission delay mainly depends on the mode used for data transmission and the reliability of the communication channel.

The optimization of delay is a complicated process, which is closely related to the working mode of the network, the routing strategy, and the reliability of the communication channel. We need comprehensive optimization.

(3) Reliable data transmission [18], [20]. In the communication process, the wireless network is affected by the quality of the channel, the attenuation of the signal and the interference of the signal, resulting in low communication reliability. Moreover, the dynamic nature of the network is strong, and its data transmission reliability is often 1-2 orders of magnitude worse than wired communication. The most commonly used methods are as follows:

(a) Transport layer based retransmission protocol to ensure reliable transmission. The most commonly used method is the Send-Wait (SW) Automatic Repeat-Request (ARQ) protocol [38]. In the SW-ARQ protocol, when the sender sends data, it waits for the receiver to return an ACK to indicate that it has received the data [38]. If the sender receives the ACK message before the timeout period arrives, it means that the packet successfully arrives at the receiver. If the sender does not receive the ACK message after the timeout expires, the sender considers that the packet has been lost and thus retransmits. The above process is repeated until the packet is successfully received by the receiver, or the number of retransmissions reaches the predetermined maximum number of times. The added load in this way is to send an ACK, and the length of the ACK packet is small compared to the data packet, so this method saves energy. However, this method will result in a larger delay, and the delay caused by multiple transmissions is even bigger.

(b) Physical layer based transmit power adjustment to ensure reliable transmission [18]. In general, the higher the transmit power of the transmitting node, the higher the Signal to Noise Ratio (SNR) of the receiving node [18]. If the SNR of the receiving signal is high, the data-receiving rate is high. Therefore, an important method to improve the reliability of data transmission is to increase the transmission power of the transmitting node. The advantage of the method for improving the reliability of data transmission by increasing the transmission power is that it has a wide application range, can operate without changing the data transmission protocol, and is advantageous for reducing delay. For example, if the transmit power is increased when the SW-ARQ protocol is used at the network layer, the number of retransmissions of the packet is reduced, and thus the delay is reduced [38].

However, the shortcoming of this method is that increasing the transmission power will reduce the lifetime of the node, thereby reducing the network lifetime.

(c) Application-based redundant coding mechanism to ensure reliable transmission [39]. The redundant coding mechanism appends some check codes to the packet. When the receiver receives the packet, it will verify the data packet. Even if there are some transmission errors in the data packet, the correction is performed by the additional redundant coding, and the correct data can be obtained, thereby making the data transmission more reliable. In general, the more redundant codes are appended to a packet, the higher the probability that the recipient can verify and correct the packet. However, due to the addition of redundant coding, the amount of data that needs to be transmitted increases and the amount of data transmitted by the node increases, thereby reducing the lifetime of the node. This method makes the wrong packet recover to a certain extent, thus reducing the probability of retransmission and reducing delay.

(d) Network layer based Opportunity Routing (OR) scheme [40]. The OR scheme is a routing method that makes full use of the broadcast characteristics of wireless communication. In the OR scheme, the sender does not select one but n nodes as receivers when sending data. Since wireless communication has a broadcast function, sender only needs to broadcast once, and n nodes can receive at the same time. As long as a node successfully receives, the data transfer is successful. Suppose that the probability of a node successfully receiving data is p, then in the OR scheme, the data transmission success rate when n nodes as receivers is $1 - (1 - p)^n$.

The OR scheme has some advantages that other routes do not have. First, the number of transmissions is reduced. The OR scheme makes full use of the broadcast function of wireless communication to reduce the number of transmissions. The sender only needs to broadcast once to achieve high data transmission reliability. Second, the OR scheme has a smaller delay. One transmission in the OR scheme is equivalent to n data retransmissions in the SW-ARQ protocol, thus reducing the waiting time for retransmission and reducing the delay, and improves the reliability of data transmission. Finally, the OR scheme reduces the number of transmissions by broadcasting and has certain advantages in terms of energy consumption.

Because the OR scheme has the above advantages, it has attracted wide attention of researchers. However, the OR scheme is not without its drawbacks. For example, excessive energy consumption is one of them. In OR scheme, the sender selects multiple candidate nodes each time, and in the process of establishing communication with these candidate nodes, the data transmission consumes a part of the energy. In addition, these candidate nodes need to consume energy to receive the same data packet. Thus, the OR scheme consumes more energy than the no-OR scheme. This is very unfriendly for wireless sensor nodes with limited power.

The current OR schemes are only applied to non-duty cycle based WSNs. In such a network, the node is always active and consumes a lot of energy. In order to reduce the energy consumption of the node, we added a duty cycle control to the OR scheme. As it joins, the node's energy consumption decreases, but at the same time, the delay increases. In this paper, we have proposed a corresponding method to solve the above problems. The main innovations of this paper are as follows:

(1) First, a Modified Opportunistic Routing (MOR) scheme is proposed to enable duty cycle control to be applied to duty cycle based WSNs. In MOR, sender reduces the number of data transfers and improves the reliability of data transmission by waiting for n awake nodes to broadcast data.

(2) Regarding the MOR scheme, since the node is random sleep/awake, it takes a long time for the sender to wait until n awake nodes, resulting in a large data transmission delay. Therefore, two duty cycle adaptive adjustment schemes are proposed to reduce delay through adjusting the node's duty cycle so that the sender can get n awake nodes faster. One is the Active Slot Uniform Distribution (ASUD) scheme and the other is Active Slot Group (ASG) scheme. In ASUD scheme, the active slot of relay nodes is evenly distributed by adaptive adjustment. The ASG scheme divides all nodes into groups. The number of nodes in each group is n. The active slots of each group are the same, and the active slots of different groups are evenly distributed.

(3) After a large number of theoretical analysis results, the ASUD and ASG scheme proposed in this paper is superior to the simple modified MOR scheme in terms of energy consumption and time delay. When the duty length $\tau = 20$, the energy consumption of the nodes in the MOR is reduced by 38.75% compared with the OR scheme, while the ASUD and ASG schemes are reduced by 41.83%.

In the following chapters, we first give the relevant work related to the content of this article in chapter II. Chapter III mainly gives the system model and problem description. Chapter IV first made a detailed analysis of the OR scheme, and then proposed the MOR scheme, the ASUD scheme and the ASG scheme. In chapter V, we conducted a detailed analysis and comparison of the proposed scheme. Chapter VI provides a comprehensive performance analysis and comparison of the proposed scheme and OR scheme. Finally, we summarize the full text in chapter VII.

II. RELATED WORK

The main contents related to the research topic of this paper are as follows: (1) Research related to Delay; (2) Research on guarantee reliability. Compared with previous studies, the OR strategy proposed in this paper is not only applicable to duty cycle based WSNs, but also requires control of the duty cycle, so that sender can wait for n wake-up candidate nodes in a short time. In addition, energy efficiency is an issue that always needs attention.

(1) Research related to delay [10], [14], [26], [40]. There are many researches related to delay, involving various

aspects of the network. For example, the network layer, the transport layer, and the application layer of the MAC layer. This paper summarizes as follows:

(a) Delay optimization of the network layer, mainly routing strategy [14], [26], [40]. Shortest routing algorithm is one of the most used routing methods in wireless sensor networks. In Shortest routing, packets are routed through multiple hops to the sink. In this process, the node always selects the node closest to the sink as the relay, so that the number of hops of the packet reaching the sink is minimized, and the delay is small.

However, the routing strategy cannot only consider the performance of delay. Energy efficiency is an important factor to consider in various strategies of wireless sensor networks. Therefore, when determining the selection criteria of the relay node in the routing strategy, it is necessary to consider multiple factors at the same time, especially the residual energy of the node and the distance from the sink. The node that has more energy remaining and is closer to the sink will be selected as the relay node. In practice, it is difficult for nodes to meet two requirements at the same time. Therefore, the actual route is often to weight multiple QoS indicators, that is, to unify the multi-objective problem into a single-objective problem, and then select a node with the largest single-object value as the relay node.

Some studies, although the main research goal is not to reduce delay, but objectively reduce the delay. For example, in some multi-path routing policies [41], a packet is routed to sink along multiple routes at the same time. As long as any route successfully reaches the sink, the route is successful. The main goal of this multi-path routing method is to ensure the security of the route to prevent the data packet from being captured during the routing process. In this way, even if some routes fail in the multi-path routing method, there will still be routes reaching the sink, thus providing a certain security. Although the main goal of this method is to improve security, it is objectively beneficial to reduce delay.

In the general routing strategy, if there is no special indication, the node is always in the awake state, so when the sender has data to send, the nodes in the forwarding nodes set can respond immediately. However, this is not the case in the duty cycle based WSNs.

In duty cycle based WSNs, the node divides the time into multiple equal slots [14]. A complete packet transmission and reception operation can be performed in one slot. One clock cycle consists of multiple slots. Nodes are active only in one slot, while sleep in other slots to save energy. Therefore, in the duty cycle based WSNs, the delay is much higher than the non-duty cycle based WSNs.

In the duty cycle based WSNs, when the sender has data to send, there may be a node in the candidate node in the sleep state, so the sender needs to wait for the node to wake up to transfer data, which greatly increases the delay. The delay of duty cycle based WSNs is several times the delay of non-duty cycle based WSNs. At the same time, its energy consumption is much lower than that of non-duty cycle based WSNs, so its lifetime is much higher than that of non-duty cycle based WSNs. In summary, duty cycle based WSNs are widely used in applications where delay requirements are not very strict.

In fact, in the duty cycle based WSNs, the selection of the relay node in the routing process is also a multi-objective optimization problem. For example, [42] classifies the routing target into a multi-objective optimization problem with energy consumption and delay. When the sender needs to transfer data, its candidate nodes can be selected from its forwarding node set. In the duty cycle based WSNs, the node closest to the sink may be in the sleep state, those nodes in the awake state may be farther away from the sink, and the nodes in the awake state may have less residual energy. At this time, the sender can immediately select the node that is in the awake state, with more residual energy and closer to the sink as the relay node. However, if you wait for a while, you may have node wake up with more energy remaining and closer to sink. Therefore, in the duty cycle based WSNs, the choice of the relay node becomes more complicated, and the target to be optimized is more.

(b) Delay optimization of the MAC layer. There are also many optimization methods for the MAC layer. First, for the duty cycle based WSNs, the main cause of delay is that when the sender needs to send data, its receiver is in sleep state. The sender needs to wait for its receiver to wake up to transfer data. This time is called sleep delay. Obviously, the most effective way to reduce sleep delay is to increase the duty cycle. If the network's duty cycle is one, the node is always in the awake state, so its sleep delay is zero. However, at this time, the node consumes the most energy, thus affecting the network lifetime.

The duty cycle of a node is mainly related to the traffic of the node. Obviously, from the perspective of energy saving, the duty cycle should be reduced as much as possible to save energy to increase network lifetime.

Based on this idea, Lee [43] also proposed a method for adaptively adjusting the node duty cycle according to the node's traffic, called Adaptable Wakeup Period (AWP). This approach is an improvement over the Same Duty Cycle (SDC) strategy used in previous sensor networks.

In the SDC network, the duty cycle of each node is the same. The near-sink node has a largest traffic and requires a maximum duty cycle. In the SDC network, the duty cycle of all nodes is set with the maximum duty cycle, which causes the node in the far-sink area to have no data to be transmitted for most of the time, which wastes energy in vain. Therefore, in the AWP method, the duty cycle of the node is determined according to the traffic of the node.If the node bears a large traffic, allocate a large duty cycle to meet the load requirements.For small traffic nodes, a small duty cycle is allocated to save energy.

Although the AWP method can save energy, the optimization of network performance is limited. In the AWP method, the nodes in the near-sink area have large traffic and allocate a large duty cycle. The nodes in the far-sink area have small traffic and allocate a small duty cycle. In fact, although this method can save energy, it does not improve the network lifetime. This is because the lifetime of the network depends on the lifetime of the nodes in the near-sink area. Therefore, saving the energy of the nodes in the far-sink area does not improve the network lifetime. In addition, due to the reduction of the duty cycle of the nodes in the far-sink area, its delay increases.

Based on the above analysis, Chen *et al.* [44] proposed a method of adaptively adjusting the duty cycle to reduce delay. Their method is almost the opposite of the AWP method. In their approach, nodes in the near-sink area use a suitable duty cycle to save energy, and nodes in the far-sink area use a large duty cycle to make full use of the remaining energy to reduce delay. This will reduce the delay without reducing the network life. Wu *et al.* [14] proposed a novel solution from another angle. Their main idea for the method of delay reduction approach through portions of nodes with larger duty cycle is: A sender has multiple forwarding nodes when sending data. As long as one node wakes up in these forwarding nodes, data forwarding can be performed. There is a surplus of energy in the far-sink area of the wireless sensor network. Therefore, if the duty cycle of some nodes is set to 1, that is, awake all the time, it is easy to get an awake forwarding node when the sender node wakes up. This approach effectively reduces delay without affecting network lifetime, which is very important for networks with limited resources [45], [46].

In addition to the value of the duty cycle has a large impact on delay, the MAC protocol also has a significant impact on delay. Fig. 1 to Fig. 3 respectively give the timeline diagrams of the three duty cycle based MAC protocols [23].

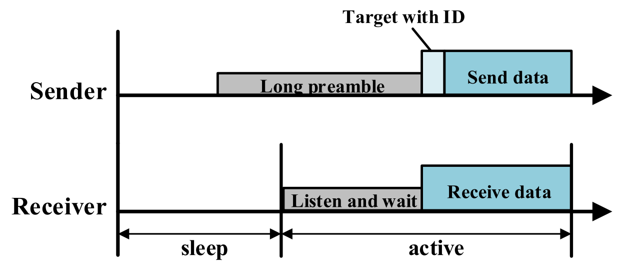

FIGURE 1. Timeline of B-MAC.

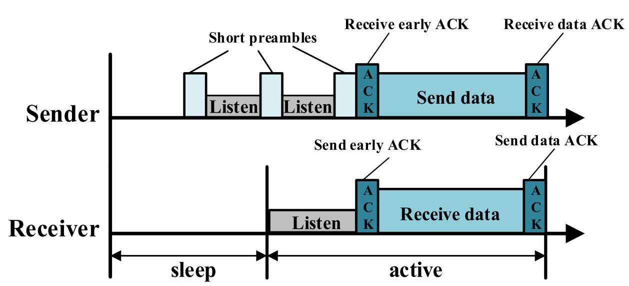

FIGURE 2. Timeline of X-MAC.

In B-MAC protocol, each node is asynchronously and periodic awake\sleep. When the sender has data to send, it sends a long preamble whose length exceeds the length of sleep to ensure that the receiver has woken up. After the receivers wake up, they keep Low Power Listening (LPL) to monitor the channel. If they listen to the preamble issued by the sender, they can establish a link and then receive the data. If there is no sender to send the packet, it will remain in the LPL state until the awake time runs out and it is transferred to sleep.

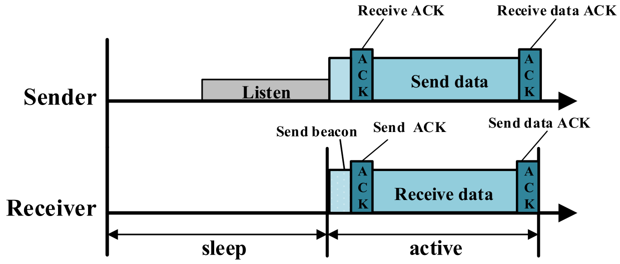

FIGURE 3. Timeline of RI-MAC.

In the B-MAC protocol, if the sender needs to send data, the sender will always maintain a preamble state until the recevier wakes up, so the energy consumed is large. To reduce energy consumption, the X-MAC protocol uses a method of replacing the long preamble with a short preamble and LPL alternately. This is equivalent to changing the state of the long preamble to the LPL state, thus saving some energy. If the receiver wakes up during the listening session of the sender, the communication link will not be established, and communication needs to be established when the sender is switched to the preamble state, thus increasing the delay.

Both the X-MAC protocol and the B-MAC protocol are protocols in which the sender initiates a communication link. In such a protocol, sender is the initiative to initiate communication, and receiver is the passive side. In fact, there is also a protocol initiated by the receiver (see Fig. 3), which is called the Receiver-Initiated MAC (RI-MAC) protocol.

In the RI-MAC protocol, the sender only listens to the channel when sending the packet, and the receiver waking up to actively initiate the beacon. In this way, the sender that needs to send data can be monitored, so that the connection can be established and communicated. In the RI-MAC protocol, sender does not need to initiate a preamble, it needs to keep listening, and each receiver will start beacon after waking up. However, in the protocol where the sender acts as the active party, the data sender is required to initiate the preamble. Therefore, the RI-MAC protocol has certain advantages in terms of energy consumption.

As can be seen from the above method, in order to establish a communication connection, one of the sender and the receiver needs to initiate the beacon, and the other must be in the listening state at the same time. Zhang *et al.* [23] proposed an Adaptive Beaconing (AB) based MAC Protocol to reduce communication delay for duty cycle based sensor networks. AB-MAC is a Receiver Initiated (RI) protocol. Unlike the previous RI-MAC protocol, which only sends beacons in the awake state, the AB-MAC protocol appropriately reduces the length of awake and send the beacon in the original sleep period, so that the sleep delay is reduced by nearly half when the energy consumption is the same. In addition, AB-MAC makes full use of the remaining energy of the node to send beacon (see Fig. 4) several times before the awake period, which further reduces the sleep delay and improves the energy efficiency.

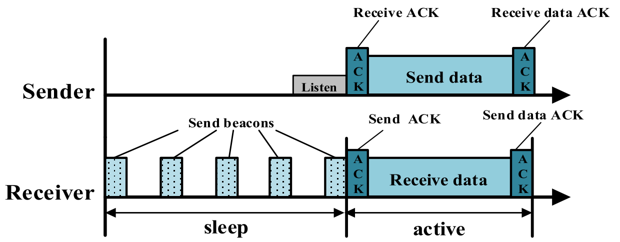

FIGURE 4. Timeline of AB-MAC.

In the above study, the duty cycle in the network is asynchronous, that is, the start time of the sleep/awake of the node is random. Therefore, the sender needs to wait for the receiver to wake up during routing, causing a sleep delay.

If the network's duty cycle is synchronized, then when the sender wakes up, its forwarding nodes must also wake up, thus reducing the delay. However, maintaining synchronization in a distributed wireless sensor network consumes node energy, and synchronization requires frequent maintenance and comes at a price.

Therefore, the researchers proposed a method of local synchronization, that is, the duty cycle between the sender and the forwarding nodes is synchronized by the self-learning method. In this way, the sender and forwarding nodes can obviously reduce the delay as long as they are roughly synchronized. This method is low in cost, easy to maintain, and has obvious effects, so it is often used.

Some studies adjust the duty cycle of nodes in the network so that the wake-up time of each hop node is consistent with the time when the data packet reaches the node. That is to say, when node A receives the data packet, it will immediately forward it to relay node B. When this packet arrives at node B, node B happens to be awake. In this case, the packet is not interrupted during the transmission and there is no sleep delay.

(2) Research on improving the reliability of data transmission. The research on the reliability of data transmission is often combined with the study of delay. This is because in wireless sensor networks, improving the reliability of data transmission will often have a certain impact on delay. Some methods to improve the reliability of data transmission will increase delay, while others will reduce delay. All methods of guaranteeing data reliability have to pay the cost of energy consumption [18].

The SW-ARQ protocol described above is a method to improve the reliability of data transmission but increase the delay. It guarantees the reliability of data transmission through a retransmission mechanism. However, due to repeated retransmissions, the delay is increased, and the energy consumed by the node due to retransmission is increased [38].

Redundancy coding at the application layer is an effective way to improve the reliability of data transmission. By adding redundant coding to the packet, the receiver can still obtain the correct data packet by correcting even if there is a bit error rate. This method improves the reliability of data transmission, but at the same time increases the delay of the node. This method improves the reliability of data transmission, but at the same time increases the delay of the node. The reason is that redundant coding increases the packet length of the node, which makes the network transmission time longer, and the network congestion increases, which eventually leads to the increase of delay. However, the increased delay in this method is much smaller than the retransmission mechanism.

Improving the transmit power of a node is another effective way to improve the reliability of data transmission. As the sender's transmit power increases, the receive rate of the receiver increases. This method not only improves the reliability of data transmission, but also reduces delay compared to other methods. This is because it directly improves the reliability of the communication channel.

Opportunistic routing [40] is a broadcast-based routing method to improve the reliability of data transmission while reducing delay. It is achieved by the following methods.

Sender determines a candidate set which is come from Forwarding Set (FS). The nodes in the FS need to meet two conditions. First, they must be within the transmission range of the sender, that is, the packet transmission can be performed with the sender. Second, the distance between the receiver and the sink should be closer than the distance between sender and the sink. Otherwise, the packets may gradually move away from the sink. The nodes in the candidate set are those in the FS that are close to the sink and have high reliability.

When the sender transmits data, the data packet is sent to all nodes in the candidate set by means of broadcast transmission. As long as any node in the candidate set receives the data, the sender is sent successfully. Retransmission is only performed when no candidate nodes receive data, and this probability is very small. Therefore, the probability of retransmission is small, which can effectively reduce delay [40]. It can be seen that when the broadcast transmission method is adopted in a network with low reliability, only when multiple receivers do not receive the data packet, retransmission is caused. Therefore, the number of retransmissions can be effectively reduced.

III. SYSTEM MODEL AND PROBLEM STATEMENT

A. THE NETWORK MODEL

Regarding the network model, we refer to the relevant information in [40]. We consider a circular network with a radius of R and a sink node at the center of the circle. The sensor nodes are evenly distributed in the network with a density of ρ. All sensors have no difference except where they are located.

The sensor node periodically collects relevant information in the vicinity, simply processes the information, and combines it with other control information (such as the serial number of the data packet mentioned above, redundant code), which is called a data packet. When appropriate, the node will send packets to the sink through other nodes as relays. After receiving the data packet, the sink node processes and analyzes these data packets and provides corresponding feedback. In this network, the sink is responsible for collecting and organizing all the information and needs to remain awake all the time. As for the sensor nodes in the network, the wake-up time is different when using different routing methods, which will be explained in the following chapters.

In this network model, the lifetime of the network is defined as the death time of the first node that died because of energy exhaustion. We suppose that the first dead node in the network is node A. After node A dies, the data that should have been collected by it may require node B to collect. The amount of data that node B needs to collect and transmit increases, the energy-consumed increases with the amount of data, and the time at which node B dies is advanced. If there is no node B, then this part of the data will not be collected after the death of node A, and the sink will lose control of the situation near node A.

Similarly, after the death of the node A, the data packet originally transferred by the node A needs to be forwarded by the node C, the number of data packets forwarded by the node C increases, and the consumed energy also increases. If node C does not exist, then this part of the packet will not be forwarded, and will not be received by sink. When the first dead node appeared, the death rate of the entire network increased, and the sink gradually lost control of the network. Therefore, we define the network's death time as the time when the first node dies, because before this, the network is complete and the sink can receive information from all nodes in the network.

B. RELIABILITY MODEL

In WSNs, data transmission is often unreliable, which makes reliability an important indicator for evaluating WSNs. According to [18], we can use the following formula to calculate the reception rate between two nodes:

$$par_{(d)} = \left(1 - \frac{1}{2}exp^{-\frac{SNR_{(d)}}{2} \times \frac{B_N}{R_D}}\right)^{8f} \tag{1}$$

We call it Packet Acceptance Rate (PAR), where, d represents the distance between two nodes, f is the size of a data packet (in bytes), B_N represents the noise bandwidth, and R_D represents the data rate. In this paper, B_N and R_D are equal to 30 kHz and 19.2 $kbps$, respectively.

$SNR_{(d)}$ represents the Signal-to-Noise Ratio (SNR) when the distance between two nodes is d [47], which can be expressed as:

$$SNR_{(d)} = P_t - PL(d) - P_n \tag{2}$$

Where P_t represents the transmit power of the node, P_n represents the background noise of the node, and according to [48], its value is $-115dBm$. $PL(d)$ represents the path loss of the node when the distance between two nodes is d. It can be expressed as:

$$PL(d) = PL(d_0) + 10n \cdot \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{3}$$

Where d_0 represents the reference distance, $PL(d_0)$ represents the path loss of the node at this distance, n represents the path loss exponent, and X_σ is a random variable associated with the time function. We replace it with a constant. In this paper, the reference distance $d_0 = 1m$, the path loss index $n = 2$.

We use P_k to indicate the probability that a packet sent by a node is successfully received by a sink, where k represents the number of hops, its value can be expressed:

$$P_k = par_1 \cdot par_2 \cdot par_3 \cdot \cdots \cdot par_k \tag{4}$$

Where par_i indicates the packet acceptance rate at the ith hop, and we use hop_i to represent this hop.

C. ENERGY CONSUMPTION MODEL

In this chapter, we present the model of the node's energy consumed due to the transmission of data packets, with reference to [47].

In this model, the energy consumed by the node is determined by the power at which the node transmits the data packet and the duration of the packet transmission. In this paper, we only consider the energy consumption when a node sends packets, receives packets, sends ACK packets, and CTS packets. The energy consumed by the node when transmitting other data packets is negligible and is not included in the scope of consideration. We use C^S to indicate the length of the packet, and N^S to indicate the number of packets sent by the node.

We multiply N^S by C^S to get the length of the data sent by the node. This value is divided by the data transmission rate R_D to obtain the duration of data transmission. Finally, we multiply this time by the power of the transmitted packet to get the energy consumed by the node due to the sending of the packet:

$$E^S = P_t \cdot C^S \cdot N^S / R_D \tag{5}$$

Similarly, we can get the energy consumed by the node to receive data packets, send ACK packets and CTS packets:

$$E^R = P_r \cdot C^R \cdot N^R / R_D \tag{6}$$

$$E^{ACK} = P_t \cdot C^{ACK} \cdot N^{ACK} / R_D \tag{7}$$

$$E^{CTS} = P_t \cdot C^{CTS} \cdot N^{CTS} / R_D \tag{8}$$

The superscript R indicates that the node receives the data packets; the superscript ACK indicates that the node sends the

ACK packets, and the superscript *CTS* indicates that the node sends the CTS packets. P_r represents the power of the node receiving the data packet, and its value is:

$$P_r = P_t - PL(d) \tag{9}$$

In summary, the total energy consumed by a node to transmit packets is:

$$E^{TP} = E^S + E^R + E^{CTS} + E^{ACK} \tag{10}$$

In this paper, the energy consumed by the node to maintain Low Power Listening (LPL) is also included, and the specific calculation will be given later.

D. PROBLEM STATEMENT

In this paper, we present three different optimization strategies for the OR scheme. All three strategies add a duty cycle control mechanism to the OR scheme. In order to be able to analyze and compare them, some criteria need to be determined first. When determining the optimization goal, we refer to [18], including minimizing the delay of the node, maximizing the reliability of the node and the lifetime of the network.

(1) Minimize the end-to-end delay. The smaller the end-to-end delay of the node, the faster the packet reaches the sink, and the faster the sink can grasp the changes in the network and respond. The end-to-end delay is the accumulation of the delay of each hop. The smaller the hop count and the delay of each hop, the smaller the end-to-end delay.

We use D_i to represent the delay of the node one the hop_i, then the end-to-end delay of node A can be expressed as:

$$min\,(D_A) = min(\sum_{i=1}^{k} D_i) \tag{11}$$

Where k is the number of hops from the node to the sink. In general, the hop count k and the delay of each hop (D_i) cannot be taken to the minimum value at the same time. In this case, we need to strike a balance between the two to minimize the end-to-end delay.

(2) Maximize the reliability of the node. The reliability of a node refers to the possibility that a packet sent by this node can be received by sink. In WSNs, packet exchange between nodes is often unreliable, and this unreliability is gradually amplified as the number of packet forwarding increases. The environment in which the network is located is generally unstable, which further exacerbates the unreliability of the nodes.

In WSNs, we expect the reliability of the nodes to be as high as possible. The higher the reliability of the node, the lower the probability of packet retransmission and the lower the energy consumed. The reliability of a node is obtained by the PAR of each hop. In order to make the reliability of the node as large as possible, on the one hand, it is necessary to ensure that the PAR of each hop node is as large as possible; on the other hand, the hop count is required to be as small as possible. In summary, the reliability of the node can be expressed as:

$$max\,(P_A) = max(\prod_{i=1}^{k} par_i) \tag{12}$$

Where k is the hop-count and par_i is the PAR of ith hop. In the actual network, it is difficult to ensure that the PAR of each hop can get the maximum value when the hop count is taken to the minimum value. At this point, we can combine the two to get the maximum node reliability.

(3) Longest network lifetime. In the previous section, we defined the lifetime of the network as the time at which the first dead node appeared. When the initial energy of the node is the same, the slower the energy consumption of the node, the longer the lifetime of the network. Therefore, maximizing network life, that is, minimizing the energy consumption of the node. We suppose that the initial energy of all nodes in the network is E_{ini}, the energy consumed by the node in each clock cycle is e, and the lifetime of the network is represented by L:

$$max\,(L) = \frac{E_{ini}}{min(e)} \tag{13}$$

In the actual network, it is difficult to find an optimization solution that meets the above three points. More often, we weighed among the above three, and finally found a compromised optimal solution.

IV. THE DESIGN OF DCAAOR SCHEME

A. RESEARCH MOTIVATION

When analyzing WSNs, it was found that the sensor nodes were carrying out unreliable packet transmission. Due to factors such as environment, distance, and the sensor itself, when node A sends a packet to node B, node B can only successfully receive the packet with a certain probability. We call this probability as Packet Acceptance Rate (PAR). The probability that node B did not successfully receive the packet is called Package Error Rate (PER). General research shows that when node A sends a packet to node B, the PAR is generally less than 0.9. That is to say, every time a node sends 10 packets, at least one packet will be lost.

We suppose that packets sent by the most edged nodes of the network can reach the sink after H hops. Then, the probability that the packet can be successfully received by the sink is:

$$P_i = \prod_{i=1}^{H} p_i \tag{14}$$

Where p_i represents the PAR of the node on the hop_i.

We suppose that the PAR for each hop can reach 0.9 (actually, often not). When $H = 20$, the end-to-end reception rate of the nodes in the network is as shown in Fig. 5. As the number of hops increases, the end-to-end reception rate of the nodes decreases significantly. The probability that a packet sent by a node at the edge of the network can be received

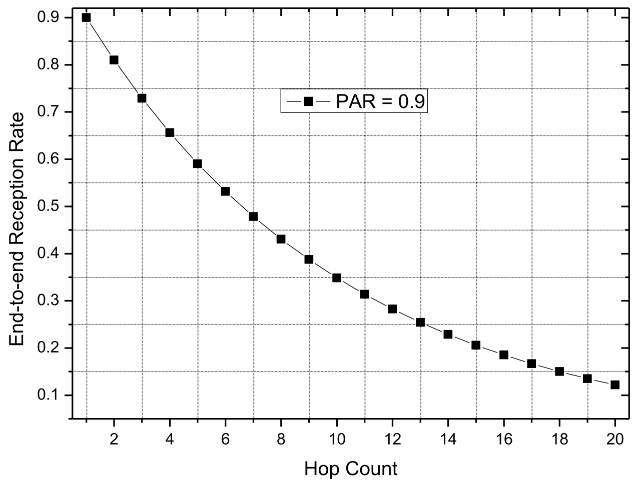

FIGURE 5. End-to-end reception rate when PAR is equal to 0.9.

by the sink is approximately 0.12, which is obviously very disadvantageous.

For those packets that have not been successfully received, we also need to resend. Even if it is resent, the probability of the packet being successfully received is still very low.

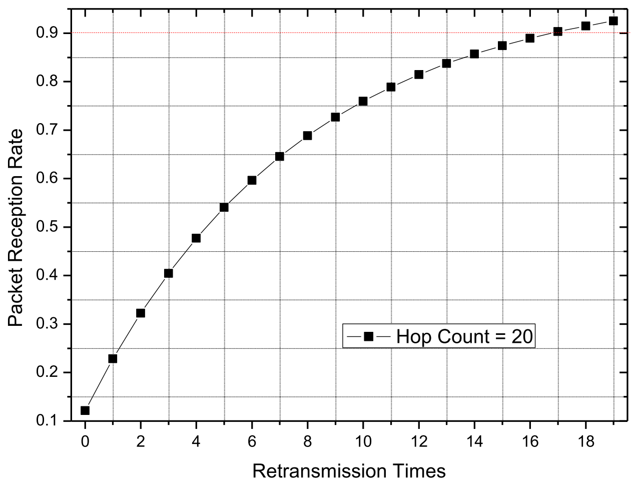

FIGURE 6. Reception rate of packet after retransmission.

Fig. 6 shows the situation where the node located in the edge area of the network resends the data packet. It can be seen that even if it is retransmitted 16 times, more than 10% of the data packets are not received by the sink.

Because the success rate of transmission between nodes is not high, the data packet may need to be retransmitted multiple times. On the one hand, the transmission time is too long; the data packet loses real-time performance. On the other hand, multiple retransmissions consume a lot of energy, which is very disadvantageous for WSNs with limited energy.

In order to improve this situation, scholars have done a lot of research, and have achieved good results. Opportunistic Routing (OR) scheme is one of them.

In simple terms, OR scheme is to change the original one-to-one transmission to one-to-many transmission. In a non-OR route, node A will only send packets to a relay node B. In OR scheme, node A selects n nodes from all the nodes that can become its relay nodes. We call the set of these n nodes the candidate set S of node A. When node A sends a packet, it sends the exact same packet to all nodes in the candidate set. Once a node in the candidate set receives a packet, it sends an ACK packet to inform the node with a lower priority than it does. Once a node receives an ACK from a node with a higher priority than itself, it will immediately discard the received packet. Eventually, the packet will be forwarded by the highest priority among all the nodes that received the packet (and an ACK is sent to node A to confirm that the packet was successfully received). From a macro perspective, the packet is still forwarded to the sink through multiple relay nodes as before. However, from a microscopic point of view, the data packets originally received by a node become shared by n nodes.

We suppose that there are three nodes in the candidate set of node A, which are node a, node b and node c, respectively. The priority is $a > b > c$. Fig. 7 gives several cases where the nodes in the candidate set receive the data packet.

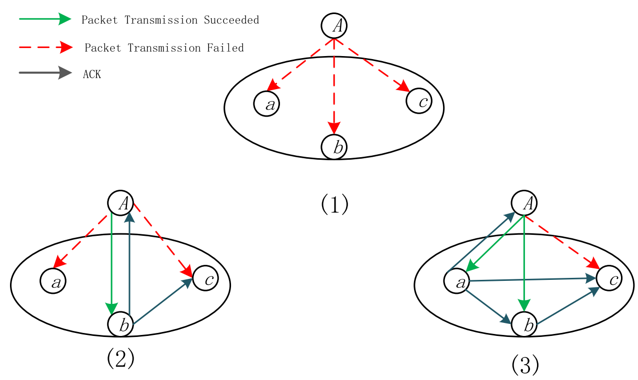

FIGURE 7. Three cases in which a candidate node receives packets.

In case (1), no candidate node receives the data packet, and node A does not receive the ACK packet sent back. Therefore, in the next clock cycle, node A will resend the same data packet.

In case (2), only node b receives the packet. When node b receives the packet, it immediately sends an ACK to the node with lower priority than itself. At the end of a clock cycle, node b does not receive an ACK from a higher priority node. Therefore, the packet will eventually be forwarded by it. At the same time, node b sends an ACK to node A. After node A receives this ACK, it will not retransmit the packet.

In case (3), multiple nodes in the candidate set successfully receive the data packet, the data packet is forwarded by the node with the highest priority among the nodes, and the other nodes that receive the data packet will directly drop the data packet.

Assume that the one hop reception rate is p_i in a non-OR route. After using the OR scheme, there are n candidate nodes, and the reception rate is increased to $1-(1-p_i)^n$. Taking the previously described network as an example, when the number of candidate nodes is $n=3$, the PAR of a single hop changes from 0.9 to 0.999; the end-to-end reception rate of the nodes at the network edge changes from 12.16% to 98.02%. By using OR scheme, the receiving rate of nodes in the network is greatly improved, and the probability of packet retransmission is greatly reduced, which is especially suitable for WSNs with low reception rate.

In the OR scheme, each sender has multiple candidate nodes as receivers. This hop data transmission is successful as long as any node in the candidate set successfully receives the data packet. This greatly improves the performance of WSNs.

The advantage of the OR scheme is obvious, but at the same time, the disadvantages are also outstanding.

The first is that the sensor node is always awake. Most of the time, the nodes are transmitting data for only a small fraction of the time. Long-term listening brings a lot of energy consumption, which is a fatal flaw for sensor nodes with limited energy.

In addition, since the transmission method in the OR scheme is one-to-many, this means that the data packet that originally only needs to be received once needs to be received n times. The energy consumption of this part is about n times that of the non-OR scheme. For those networks with high packet loss rate, in order to increase the reliability of the node, it is generally necessary to select more candidate nodes. The more candidate nodes, the more energy is consumed.

In order to reduce the energy consumption of the nodes and increase the lifetime of the network, we have introduced a classic approach to saving energy - adding duty cycle control. Duty cycle indicates the ratio of the time the node is in the awake state to the clock period. We suppose that the duty cycle of a node is $1/\tau$, that is, we divide the entire clock cycle into τ slots, the node wakes up in a random one of the slots, and after a few slots, it goes to sleep (not necessarily 1 slot). We call this method the Modified Opportunistic Routing (MOR) scheme. The energy consumed by the node to sleep is much less than when the awake is maintained, thus saving energy.

With the addition of the duty cycle control, the energy consumption of the node is significantly reduced, but it also brings new problems. When the sender needs to transmit a data packet, there is a high probability that there is no n relay nodes in the awake state. In this case, we need to wait for a while until the number of nodes in the awake state reaches n. This brings a huge one-hop delay to the node, which in turn causes a huge end-to-end delay. In WSNs, the energy consumption of nodes and the end-to-end delay of nodes are our focus, and we must not lose sight of them. Therefore, we need to find an optimized method to reduce the delay of the node as much as possible.

After the duty cycle control is added, the delay of the node becomes large. The reason is that the sender spends a lot of time waiting for the n nodes to wake up. The case where the waiting time is the largest is given in Fig. 8 (we suppose that the number of candidate nodes of the node is 3).

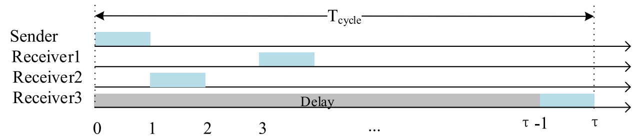

FIGURE 8. Forwarding nodes wake up randomly.

In this extreme case, the sender wakes up at the beginning of the clock cycle, but until the last slot, the N_n candidate node wakes up. We suppose that the entire clock cycle is divided into τ slots, then the maximum waiting time is $\tau-1$ slots.

Obviously, if we can control the node to wake up according to certain rules, we can control the waiting time within a certain range.

We first let all candidate nodes wake up ''uniformly'' in one clock cycle, which we call the Active Slot Uniform Distribution (ASUD) scheme. We suppose that there are N nodes in the forwarding set of node A, and one node wakes up every τ/N slots. In this case, the maximum waiting time of the node is shown in Fig. 9.

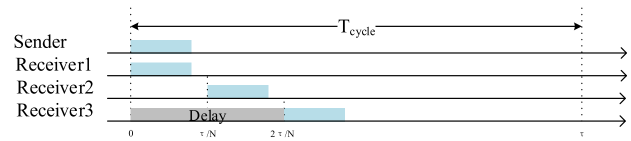

FIGURE 9. Forwarding nodes wake up evenly.

As can be seen from Fig. 9, when the sender node wakes up at the beginning of the clock cycle, the waiting time is the largest, which is $(n-1)\,\tau/N$ slots. If the sender wakes up at other times, the waiting time will be less than this value. If the sender wakes up at or after $(n-1)\,\tau/N$ slots, the waiting time is zero.

In both of the above schemes, after the node wakes up, it may need to keep waking up in the next few slots, which brings a part of the energy consumption and is unfavorable to the network. We hope that the node does not need to stay awake for a long time, and the sender node does not have to wait too long. Therefore, we proposed the Active Slot Group (ASG) scheme. In this scheme, N candidate nodes will be divided into several groups, and there are n candidate nodes in each group. We suppose that there are x groups, which will wake up evenly in one clock cycle and go to sleep after one slot (a group of nodes will wake up every τ/x slots). In this case, the maximum waiting time of the sender is shown in Fig. 10.

The sender node wakes up when the previous group of nodes enters sleep, and must wait for the next group of nodes to wake up. The waiting time at this time is $\tau/x-1$ slots.

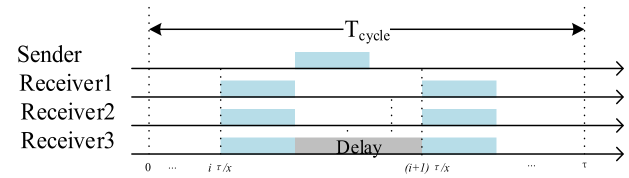

FIGURE 10. Forwarding nodes wake up evenly by group.

B. DESIGN OF THE DCAAOR SCHEME

In order to reduce the energy consumption of the nodes in the OR scheme, we have added the duty cycle control. With the addition of the duty cycle control, the energy consumption of the node decreases while the delay increases. In this case, we propose the Duty Cycle Adaptive Adjustment based Opportunistic Routing (DCAAOR) scheme, which is expected to minimize the impact on the delay while reducing the energy consumption of the node.

According to the different wake-up rules of nodes, we propose three DCAAOR schemes, which are Opportunistic Routing (MOR) scheme, Active Slot Uniform Distribution (ASUD) scheme and Active slot group (ASG) scheme.

In the Modified Opportunistic Routing (MOR) scheme, the wake-up time of a node is random. We divide the entire clock cycle into τ slots, and the nodes may wake up in any slot, and must wake up only in one slot.

Modified Opportunistic Routing (MOR) scheme can be described by Algorithm 1.

The meaning of the symbolic representation in the algorithm is as follows.

(1) F_A: The forwarding set of the sender node A;

(2) C_A: The candidate set of sender node A;

(3) hello message: Message sent by node when waking up;

(4) GTS (Go to Sleep) message. Let the node go to sleep to save energy.

(5) ACK (Acknowledgement) message. Message returned by Receiver after successfully receiving packets.

(6) ETS (End to Send) message. After receiving the ACK message, the Sender indicates that the data is successfully sent by broadcasting the ETS message.

In the Active Slot Uniform Distribution (ASUD) scheme, nodes are uniformly awake in τ slots. We suppose that there are N nodes in the forwarding set of a node. Then, from the beginning of the clock cycle, every τ/N slots will wake up one node.

During the first round of data transfer, the node still does not know when it should wake up. So, as in algorithm 1, let all the nodes wake up randomly and note the order in which the nodes wake up. We number all nodes from 0 to $N-1$ in the order in which the nodes wake up in the first round.

Starting from the second round, the nodes will wake up and sleep in order. In order to keep the nodes awake as much as possible, we can also adjust the order of the nodes after each round of data transmission.

Active Slot Uniform Distribution (ASUD) scheme can be described by Algorithm 2.

Algorithm 1 MOR Scheme

The action of Sender

For the node that wants to send packets (such as A) **Do**
  Determine F_A;
  C_A = Null; // The candidate set is empty at beginning.
  C_count=0; // Number of candidate nodes is 0
  While received a hello message sent by node B in F_A
    C_count++; // Candidate nodes is increased by 1
    $C_A = C_A \cup B$;
    IF C_count $\geq n$ //n candidate nodes awake
      IF node A is awake
        Broadcast packets to C_A; // Data broadcasting
        Broadcast GTS message; // Stay asleep to save energy
        break;
      ELSE
        IF C_count n // Too many nodes awake
          Send a GTS message to node B; // To save energy
          C_count–;
        End IF
      End IF
    End IF
  End
  IF node A received an ACK message from node C of C_A
    node A broadcast ETS message; // Packets successfully sent
  End if
End for

The action of Recevier

When node B awake **Do**
  node B broadcast hello message;
  IF node B receives a GTS or ETS message from a sender
    node B enters sleep state; // To save energy
  ELSE
    node B keeps awake;
  End If
  IF node B receives packets
    Broadcast ACK message;
  End if
  IF node B receives ETS message
    End of reception; //Packet transmission succeeded
  ELSE
    Retransmit; // In the next round
  End if
End

The symbolic representation in this algorithm has the same meaning as algorithm 1.

As in the Active Slot Uniform Distribution (ASUD) scheme, the nodes in the Active Slot Group (ASG) scheme are also awakened in the clock cycle in a certain order.

The difference is that in the ASG scheme, we need to group the nodes first. We suppose that there are a total of N forwarding nodes, and each time a data transmission requires n candidate nodes, then the nodes can be divided into $\lceil N/n \rceil$ groups.

When appropriate, we need to select some of the nodes that have been awakened before to join the last group.

If each group of nodes is treated as a node, then the receiver wakes up in exactly the same way as the ASUD scheme. The difference is that when the sender in the ASG scheme wakes

Algorithm 2 ASUD Scheme

The action of Sender

For the node that wants to send packets (such as A) **Do**
Determine F_A;
When node A awake **Do**
GET the wake-up time of node A t;
IF t $(n-1)\tau/N$ //Less than n candidate nodes
Send packets at $(n-1)\tau/N$ slot; // Wait a while
Broadcast GTS message; // Stay asleep to save energy
ELSE
Send the packets immediately;
Broadcast GTS message; // Stay asleep to save energy
End IF
END
IF node A received an ACK message from node C of C_A
node A broadcast ETS message; // Packets successfully sent
End if
End for

The action of Recevier

For each node (such as B) in F_A **DO**
GET the number of node B i;
GET current slot t;
IF $t = i\tau/N$
node B wakes up;
ELSE IF $t = (i+n)\tau/N$ or $t = \tau$ or received ETS message
node B enters a sleep state; //To save energy
End IF
IF node B receives the packets
Broadcast ACK message;
End if
IF node B receives ETS message
End of reception; //Packet transmission succeeded
ELSE
Retransmit; // In the next round
End if
Adjust the number of the node, $i = (i+m) mod N$;
//m can be any number from 1 to $N-1$
End

Algorithm 3 ASG Scheme

The action of Sender

For the node that wants to send packets (such as A) **Do**
Determine F_A;
When node A awake **Do**
GET the wake-up time of node A t;
$k = \lfloor \frac{tx}{\tau} \rfloor$; //Group k should be responsible for receiving
IF $k\tau/x \leq t \leq k\tau/x + 1$ or $t > (x-1)\tau/x$
Send packets immediately
Broadcast GTS messages;
ELSE
Sending packets at $(k+1)\tau/x$ slot
Broadcast GTS messages;
End IF
End
IF node A received an ACK message from node C of C_A
node A broadcast ETS message; // Successfully sent
End if
End for

The action of Recevier

For each node (such as B) in F_A **DO**
GET current slot t;
GET the number of node B i;
$x = \lceil N/n \rceil$; // Divide nodes into x groups
$j = \lfloor i/n \rfloor$; // The group number of node B
$m = nx - N$; // The number of nodes that wake up twice
IF $t = j\tau/x$ or ($i < m$ and $t = (x-1)\frac{\tau}{x}$) ;
node B wakes up;
End IF
IF$t = \tau$ or ($t = \frac{j\tau}{x} + 1$ and $j < x-1$) or received GTS
node B enters a sleep state; //To save energy
End IF
IF node B receives the packets
Broadcast ACK message;
End if
IF node B receives ETS message
End of reception; //Packet transmission succeeded
ELSE
Retransmit; // In the next round
End if
Adjust the number of the node, $i = (i+m) mod N$;
End

up, as long as the node is in the awake state, data transmission can be performed immediately.

Active Slot Group (ASG) scheme can be described by Algorithm 3.

The symbolic representation in this algorithm has the same meaning as algorithm 1.

V. THE THEORETICAL ANALYSIS OF THE PROPOSED SCHEME

In the chapter IV, we added the duty cycle control to the OR scheme and proposed the Modified Opportunistic Routing (MOR) scheme. Subsequently, in order to optimize performance, the Duty Cycle Adaptive Adjustment based Opportunistic Routing (DCAAOR) scheme was proposed. According to the wake-up rules of the nodes in the DCAAOR scheme, the Active Slot Uniform Distribution (ASUD) scheme and the Active Slot Group (ASG) scheme are proposed respectively. In this chapter, we first analyse and discuss the same performance of the three schemes, and then analyse the different performances of the three schemes in turn.

A. ANALYSIS OF THE SAME PERFORMANCE

According to the description of the network model in section III.A, we suppose that there is a WSN with radius R, which is centered on the sink node, and the sensor nodes are evenly distributed in the network with density ρ.

We suppose that the node in the network has a transmission radius of r. From the edge of the network, the entire WSN is divided into rings with a ring width r. In most cases, we cannot guarantee that the entire WSN is exactly divided evenly. Therefore, the width of the ring closest to the sink may be smaller than r. The nodes on this ring can communicate directly with the sink, and the sink is always working. Therefore, in the analysis of OR scheme and DCCOR scheme, the situation on this ring will not have a bad effect on the results.

We abstract the network after the above division, and regard the ring as a circle with the same radius as the outer radius of the ring. All the nodes on the ring are evenly distributed on this circle. According to the distance of the ring from the sink node, the nodes on these rings are called nodes on the $ring_i$ in turn, where $i = 0, 1, 2, , , m-1$ and m is the number of rings. We divide the radius r of the ring by the radius R of the entire network, and round up the result to get the number of rings, $m = \lceil R/r \rceil$.

In particular, the $ring_0$ has an inner radius of 0 and an outer radius of $R-(m-1)r$. The area of this ring is:

$$S_0 = \pi \left[R-(n-1)r\right]^2 \tag{15}$$

The number of nodes on the $ring_0$ is:

$$Q_0 = \rho\pi \left[R-(n-1)r\right]^2 \tag{16}$$

In general, the inner radius of the $ring_i$ is $R-(i-m)r$ and the outer radius is $R-(i-m-1)r$, and the area is:

$$S_i = \pi \left[R-(i-m-1)\, r\right]^2 - \pi \left[R-(i-m)r\right]^2 \tag{17}$$

Simplified to:

$$S_i = \pi \left\{2Rr + \left[2\,(i\text{-}m)+1\right] r^2\right\} \tag{18}$$

Therefore, the number of nodes on the $ring_i$ is:

$$Q_i = \rho\pi \left\{2Rr + \left[2\,(i\text{-}m)+1\right] r^2\right\} \tag{19}$$

To simplify the calculation, we suppose that the node only sends one packet to the sink per clock cycle.

After the node successfully receives the data packet sent by its outer node, it will integrate the data packet generated by itself and the received data packet, and then send it to the next hop node.

In the edge area of the network, the node only sends the data packets generated by itself, and does not need to forward the data packets of other nodes.

Therefore, for this part of the node, the number of transmitted data packets is one, and the number of received data packets is zero. Correspondingly, the number of transmitted CTS data packets is one, and the number of transmitted ACK data packets is zero.

In section III.B, we give a method for calculating the reception rate between two nodes, which we use p_i to represent. According to the analysis in section IV.A, in the OR scheme, when the number of candidate nodes is n_i, the probability of successful one hop transmission on the $ring_i$ is:

$$P_i = 1-(1-p_i)^{n_i} \tag{20}$$

The data packet received by the node on the $ring_i$ is the data packet sent on the $ring_{i+1}$ ring.

There are Q_{i+1} nodes on the $ring_{i+1}$, and each node will send Q_{i+1}^S packets.These packets will be received n_i times by the nodes on the $ring_i$. There are Q_i nodes on the $ring_i$, and the probability that each node can successfully receive the data packet is p_i. Therefore, the number of packets received on the $ring_i$ is:

$$Q_i^R = \frac{Q_{i+1} Q_{i+1}^S n_i p_i}{Q_i} \tag{21}$$

Substituting the relevant values to get:

$$Q_i^R = \left\{1+\frac{2r}{2\mathrm{R}+\mathrm{r}\left[2\,(\mathrm{i\text{-}m})+1\right]}\right\} Q_{i+1}^S n_i p_i \tag{22}$$

The data packet sent by the node on the $ring_i$ is mainly to assist the data packet forwarded by the node on the $ring_{i+1}$ ring, and the second is its own data packet. There are Q_{i+1} nodes on the $ring_{i+1}$ ring, and each node sends Q_{i+1}^S packets. These packets are received by the node on the $ring_i$ and are forwarded to the node on the $ring_{i-1}$ ring with a probability of P_i. Therefore, on average to Q_i nodes, the data packets sent by each node are:

$$Q_i^S = \frac{Q_{i+1} Q_{i+1}^S P_i}{Q_i} + 1 \tag{23}$$

Substituting the relevant values to get:

$$Q_i^S = \left\{1+\frac{2r}{2\mathrm{R}+\mathrm{r}\left[2\,(\mathrm{i\text{-}m})+1\right]}\right\} Q_{i+1}^S P_i + 1 \tag{24}$$

The CTS sent by the node on the $ring_i$ is mainly used for communication between candidate nodes. First, tell the last hop node that it is ready to receive the packet. When a node receives several data packets, it needs to send an equal amount of CTS data packets to the previous hop node in advance. The number of CTS packets in this part is equal to the number of packets received by the node on the $ring_i$. The second is to inform the next hop node that it can start receiving ACK packets (the node will return an ACK packet to the sender after successfully receiving the data packet).The number of CTS packets in this part is equal to the number of packets sent by the node on the $ring_i$. The third is to receive the number of communications of other candidate nodes.

We suppose that the priority of node A is k, and the number of CTS packets it sends is related to the situation of the packets received by the $k-1$ nodes in front of it. For the jth node of the first $k-1$ nodes, if it successfully receives the data packet, and the first $j-1$ nodes do not receive the data packet, it needs to send j CTS data packets as a response.

Therefore, the number of CTS packets sent for communication with other candidate nodes is:

$$Q_i^{CTS-cnk} = \sum_{j=1}^{k-1} jp_i\,(1-p_i)^{j-1} + (k-1)\,(1-p_i)^{k-1} \tag{25}$$

We suppose that:

$$A = \sum_{j=1}^{k-1} jp_i\,(1-p_i)^{j-1} \tag{26}$$

Then, Eq. (25) can be expressed as:

$$Q_i^{CTS-cnk} = Ap_i + (k-1)\,(1-p_i)^{k-1} \tag{27}$$

For A, we make $k-1=n$:

$$A=\sum_{j=1}^{n} \mathrm{j}\left(1-p_i\right)^{j-1} \tag{28}$$

Multiply both sides of the equation by $1-p_i$:

$$A\left(1-p_i\right)=\sum_{j=1}^{n} \mathrm{j}\left(1-p_i\right)^{j} \tag{29}$$

Subtract Eq. (29) from Eq. (28):

$$Ap_i=-n\left(1-p_i\right)^{n}+\sum_{j=1}^{n} \mathrm{j}\left(1-p_i\right)^{j} \tag{30}$$

Substituting $n=k-1$ into the above formula, there are:

$$Ap_i=-\left(k-1\right)\left(1-p_i\right)^{k-1}+\sum_{j=1}^{k-1} \mathrm{j}\left(1-p_i\right)^{k-1} \tag{31}$$

Substituting the value of Ap_i into Eq. (27):

$$Q_i^{CTS-cnk}=\sum_{j=1}^{k-1} \mathrm{j}\left(1-p_i\right)^{k-1} \tag{32}$$

Using the summation formula of the geometric series:

$$Q_i^{CTS-cnk}=\frac{1-\left(1-p_i\right)^{k-1}}{p_i} \tag{33}$$

The states of all candidate nodes are the same, so the probability that nodes are at different priorities is the same. Then, we find the number of CTS packets sent when the nodes are at different priorities, and average them:

$$Q_i^{CTS-cn}=\frac{1}{n_i}\sum_{k=1}^{n_i} Q_i^{CTS-cnk} \tag{34}$$

Simplified to:

$$Q_i^{CTS-cn}=\frac{1}{p_i}-\frac{P_i}{n_i p_i^2} \tag{35}$$

In summary, the number of CTS packets sent by the node on the $ring_i$ is:

$$Q_i^{CTS}=Q_i^{R}+Q_i^{S}+Q_i^{R}\left(\frac{1}{p_i}-\frac{P_i}{n_i p_i^2}\right) \tag{36}$$

In three different DCAAOR schemes, the number of ACK packets sent by the node is different due to the different rules of node wake-up. We can divide the ACK packet sent by the node into two parts. The first part is the ACK packet sent by the node in the OR scheme, and the second part is the ACK packet sent after the duty cycle control is added. Here we first consider the number of ACK packets in the first part, the second part we will discuss later.

After the node on the $ring_i$ successfully receives the data packet, it sends ACK packets to inform the node with lower priority than it does, so that these nodes discard the received data packet (if received). Therefore, the number of ACK packets sent by the node on the $ring_i$ is:

$$Q_i^{ACK}=Q_i^{R}\frac{1}{n_i}\sum_{k=1}^{n_i}\left(1-p_i\right)^{k-1} \tag{37}$$

Simplified to:

$$Q_i^{ACK}=Q_i^{R}\frac{P_i}{n_i p_i} \tag{38}$$

Combined with the energy consumption model in section III.C, we can calculate the specific energy consumption when the node transmits the packets.

However, in the above calculations, we still have an unknown number, which is the transmission radius of the node. In the previous analysis, we know that the transmission radius of a node determines how far each hop advances and affects the number of hops from the node to the sink. The hops has different effects on the delay and energy consumption of the node. Therefore, it is not possible to specify a value of the transmission radius. In order to find the most representative transmission radius, we use the following method.

General research [18] shows that when a node determines a candidate set, it is selected from all nodes with a reception rate between 0.1 and 0.9. When the node S sends a data packet, the area where the node with the success rate between 0.1 and 0.9 is located is called the forwarding region. The set of nodes on the forwarding region is called forwarding set (FS), and the node S selects n nodes from the FS to form a set of candidate nodes.

According to the description of the reliability model in section III.B:

$$par_{(d)}=\left(1-\frac{1}{2}exp^{-\frac{SNR_{(d)}}{2}\times\frac{B_N}{R_D}}\right)^{8f} \tag{39}$$

$$SNR_{(d)}=P_{tdB}-PL\left(d\right)_{dB}-P_{n\,dB} \tag{40}$$

$$PL\left(d\right)=PL\left(d_0\right)+10n\cdot\log_{10}\left(\frac{d}{d_0}\right)+X_\sigma \tag{41}$$

We can reverse the distance between two nodes:

$$d=d_0 10^{\frac{P_t-P_n+\frac{2R_D}{B_N}\log_e\left(1-\sqrt[8f]{par_{(d)}}\right)-PL(d_0)-X_\sigma}{10n}} \tag{42}$$

We use r_{os} to represent the transmission radius when the receiver rate is 0.1, and r_{is} is the transmission radius when the receiver rate is 0.9, then:

$$r_{is}=d_0 10^{\frac{P_t-P_n+\frac{2R_D}{B_N}\log_e\left(1-\sqrt[8f]{0.9}\right)-PL(d_0)-X_\sigma}{10n}} \tag{43}$$

$$r_{os}=d_0 10^{\frac{P_t-P_n+\frac{2R_D}{B_N}\log_e\left(1-\sqrt[8f]{0.1}\right)-PL(d_0)-X_\sigma}{10n}} \tag{44}$$

According to the above formula, the range of the transmission radius of the node S under different transmit powers can be obtained, as shown in Fig. 11. When the transmitting power of the node S is small, the receiving node is closer to the node S, and the forwarding region is smaller. Conversely, when the transmit power of the node S is large, the receiving

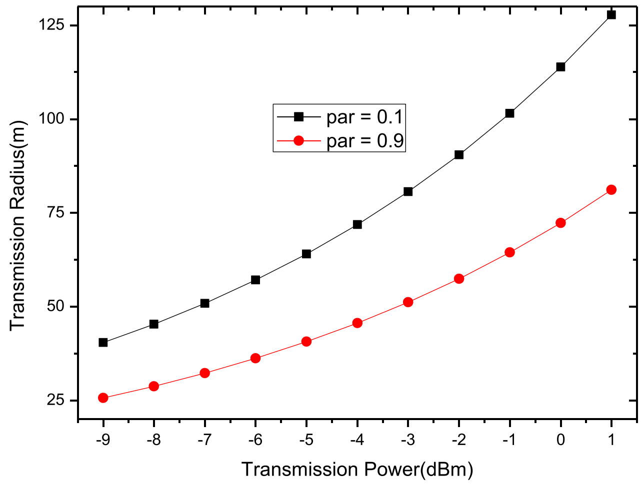

FIGURE 11. Maximum and minimum transmission radius of the node.

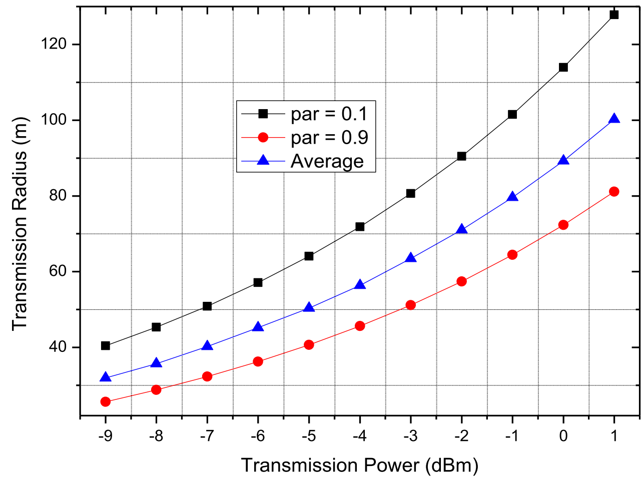

FIGURE 12. Average transmission radius of the node.

node is farther away from the sink, and the forwarding region is larger.

According to the previous analysis, the forwarding region of node S is a ring with r_{os} as the outer radius and r_{is} as the inner radius. We divide the forwarding region into several small rings with a ring width of 1 meter. For the convenience of calculation, we round down r_{os} and round up r_{is}. We call these small rings $0, 1, \ldots, (\lfloor r_{is} \rfloor - \lfloor r_{os} \rfloor - 1)$ rings, where the inner radius of the $ring_k$ is $\lfloor r_{os} \rfloor + k$, the outer radius is $\lfloor r_{os} \rfloor + k + 1$.

The area of the $ring_k$ is:

$$S_k = \pi \left(\lfloor r_{os} \rfloor + k + 1 \right)^2 - \pi \left(\lfloor r_{os} \rfloor + k \right)^2 \tag{45}$$

Simplified to:

$$S_k = \pi \left[2 \left(\lfloor r_{os} \rfloor + k \right) + 1 \right] \tag{46}$$

The number of nodes on the $ring_k$ is:

$$Q_k = \rho \pi \left[2 \left(\lfloor r_{os} \rfloor + k \right) + 1 \right] \tag{47}$$

We suppose that the distances of these nodes from node S are $\lfloor r_{os} \rfloor + k + 1$ (distributed on the outer circle of the ring). According to Eq. (1) in section III.B, the PAR of the nodes on $ring_k$ can be obtained. We use par_k to indicate.

Therefore, the transmission radius of node S can be expressed as:

$$r_S = \sum_{k=\lfloor r_{is} \rfloor + 1}^{\lfloor r_{os} \rfloor} k \frac{Q_k par_k}{\sum_{j=\lfloor r_{is} \rfloor + 1}^{\lfloor r_{os} \rfloor} Q_j par_j} \tag{48}$$

Then, the transmission radius of the node at different transmission powers is as shown in Fig. 12:

At this time, the receiving rate between nodes under different transmit powers is as shown in Fig. 13.

In order to improve the one-hop reception rate, we arrange n candidate nodes for each node. In Fig. 14 we take $n = 2$, $n = 3$ and $n = 4$ respectively. When the number of candidate

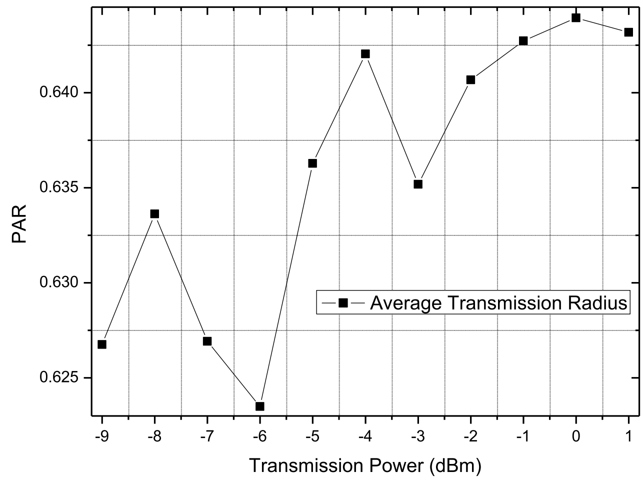

FIGURE 13. PAR when the transmission radius is averaged.

nodes is 2, the PAR of one-hop is less than 0.9. When $n = 3$, the PAR is increased to about 0.95, which is an ideal state. As n continues to increase to 4, PAR will increase by about 0.03. As the number of candidate nodes increases, the number of packets sent and received by the node increases, which will bring a lot of energy consumption. Therefore, we believe that no matter how much the transmission power is equal, when using the weighted average transmission radius as the transmission radius, we select 3 candidate nodes for each node.

A network conforms to the description of the network model in section III.A. We suppose that the network radius is $R = 1000m$, the duty length $\tau = 20$, the number of candidate nodes of the node is n = 3, and the transmission radius of the node is $r = 63.4857m$. ($pt = -3dBm$), then the whole network can be divided into 16 small rings(The networks in the collection have different node densities, the others are the same). The density of nodes in the network is not involved in the above process. Therefore, regardless of the

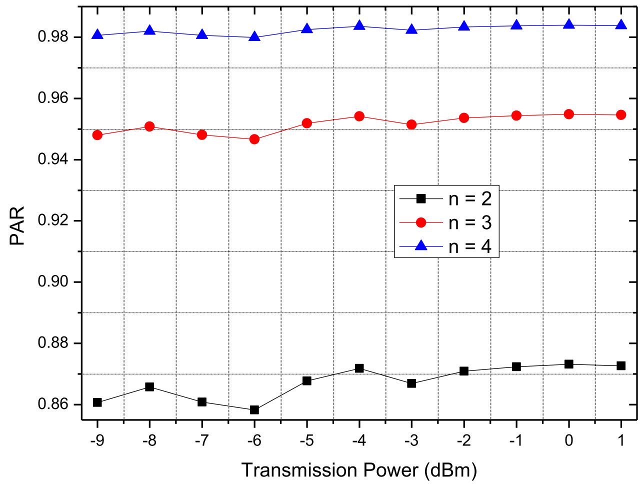

FIGURE 14. PAR when multiple candidate nodes are selected.

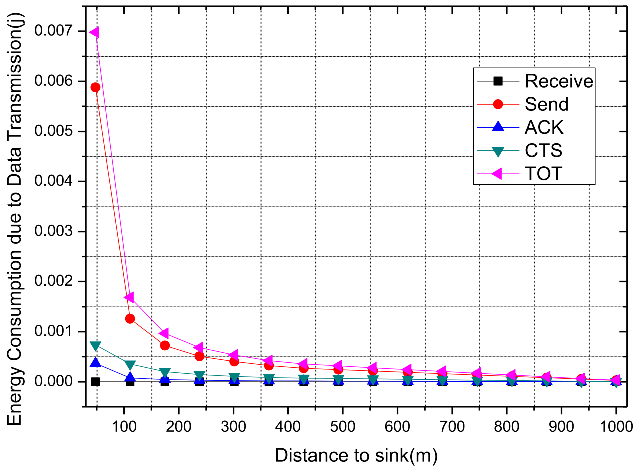

FIGURE 16. Energy consumption when a node transmits packets.

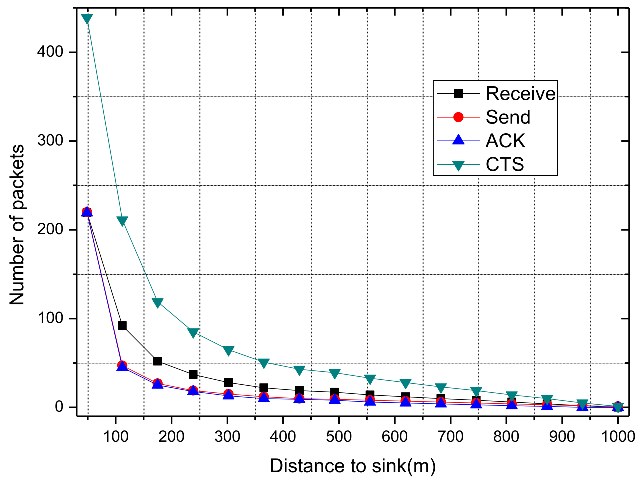

FIGURE 15. Number of packets transmitted by the node.

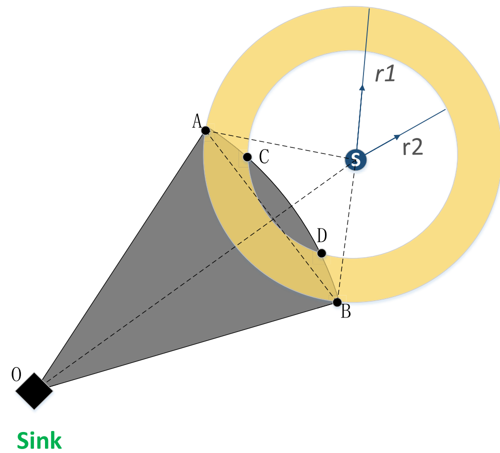

FIGURE 17. Schematic diagram of calculating the number of forwarding nodes.

density, as long as the radius of the network and the transmit power of the node are unchanged, the number of data packets transmitted by the node remains unchanged. The number of packets transmitted by the nodes on these rings is shown in Fig. 15.

According to the energy consumption model in section III.C, we can find the energy consumed by the node to transmit the data packet, as shown in Fig. 16.

In the process of calculating the transmission radius of node S, we calculate the area of the forwarding region. However, we want the packet to be forwarded to the sink as soon as possible, so the forwarding region above does not represent the area where the forwarding nodes are located. We need to recalculate this part of the area to get the area of the forwarding region, and then the number of forwarding nodes, which is the basis for calculating the delay and listening time of the node.

In Fig. 17, the distance between node S and sink is d. Take the node S as the center and draw a circle with the radius of r_{os} to get the circle 1. The probability that the node located outside the circle 1 receives the data packet that sent by the node S is less than 0.1. Take the node S as the center and draw a circle with the radius of r_{is} to get the circle 2. The probability of a node in circle 2 receiving a packet is greater than 0.9.

With sink as the center and $d - x$ as the radius (x represents the minimum value of the distance reduction of the node S from the node sink after each hop), and the circle O is obtained. Circle O intersects circle 1, circle 2 at four points A, B, C and D. The part of the ring formed by circle 1 and circle 2 that overlaps with circle O is the position of the node in the forwarding set of node S. In order to facilitate the calculation of the area of the overlap, we made the following auxiliary lines and points in Fig. 17, connect AS, BS, OS and AB respectively.

We need to find the area of the overlap shown in Fig. 17, which is equal to the area S_1 where the circle O intersects the circle 1 minus the area S_2 where the circle O intersects the circle 2.The radius of circle O and circle 1 are $d - x$ and r_1, respectively, and the distance between node S and sink is d. By means of the cosine function in OAS, we can conclude that the two central angles corresponding to the string AB are:

$$\alpha_S^1 = 2acos\frac{r_{os}^2 + d^2 - (d-x)^2}{2dr_{os}} \tag{49}$$

$$\alpha_O^1 = 2acos\frac{(d-x)^2 + d^2 - r_{os}^2}{2d\,(d-x)} \tag{50}$$

The area of the fan corresponding to the two central angles is:

$$S_{\alpha_S} = \frac{1}{2}\alpha_S^1 r_{os}^2 \tag{51}$$

$$S_{\alpha_O} = \frac{1}{2}\alpha_O^1 (d-x)^2 \tag{52}$$

The two triangle areas corresponding to the two central angles are:

$$S_{\triangle SAB} = \frac{1}{2} r_{os}^2 sin\alpha_S^1 \tag{53}$$

$$S_{\triangle OAB} = \frac{1}{2}(d-x)^2 sin\alpha_O^1 \tag{54}$$

In summary, S_1 is equal to the area of the two sectors minus the sum of the areas of the two triangles:

$$S_1 = \left(S_{\alpha_S} + S_{\alpha_O}\right) - (S_{SAB} + S_{OAB}) \tag{55}$$

Simplified to:

$$S_1 = \frac{1}{2}\left[\begin{array}{l} r_{os}^2\left(\alpha_S^1 - sin\alpha_S^1\right) \\ +(d-x)^2\left(\alpha_O^1 - sin\alpha_O^1\right) \end{array}\right] \tag{56}$$

Similarly, the area of S_2 is:

$$S_2 = \frac{1}{2}\left[\begin{array}{l} r_{is}^2\left(\alpha_S^2 - sin\alpha_S^2\right) \\ +(d-x)^2\left(\alpha_O^2 - sin\alpha_O^2\right) \end{array}\right] \tag{57}$$

Where:

$$\alpha_S^2 = 2acos\frac{r_{is}^2 + d^2 - (d-x)^2}{2dr_{is}} \tag{58}$$

$$\alpha_O^2 = 2acos\frac{(d-x)^2 + d^2 - r_{is}^2}{2d\,(d-x)} \tag{59}$$

The area of the forwarding region is:

$$S_{FS} = S_1 - S_2 \tag{60}$$

The number of nodes in this region is the number of nodes in the forwarding set:

$$N_{FS} = \rho S_{FS} \tag{61}$$

In summary:

$$N_{FS} = \frac{1}{2}\rho\left\{\begin{array}{l} r_{os}^2\left(\alpha_S^1 - sin\alpha_S^1\right) - r_{is}^2\left(\alpha_S^2 - sin\alpha_S^2\right) \\ +(d-x)^2\left[\left(\alpha_O^1 - sin\alpha_O^1\right) - \left(\alpha_O^2 - sin\alpha_O^2\right)\right] \end{array}\right\} \tag{62}$$

In network A, the number of forwarding nodes of nodes at different densities is shown in Fig. 18. In particular, at the hop closest to the sink, the node can communicate directly with the sink. The size of the forwarding set is one, and the number

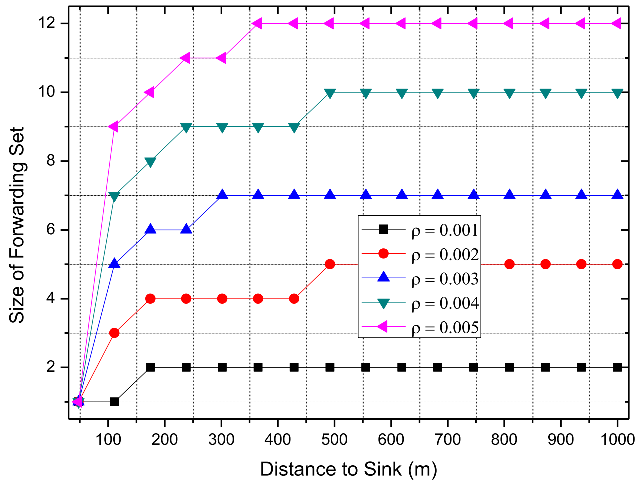

FIGURE 18. **The greater the density, the larger the forwarding set.**

of candidate nodes is one. When the distance from the node to the sink is the same, the larger the density of the nodes in the network, the larger the number of forwarding nodes. This is because in the same area, the higher the density, the more nodes. When the nodes in the network have the same density, the farther away from the sink, the greater the number of forwarding nodes. This is because the farther away from the sink, the larger the area of the forwarding region, the greater the number of nodes.

So far, we have discussed the same performance in three different DCAAOR schemes. Below, we will analyze the three schemes separately. For the convenience of description, we make the following provisions:

We suppose that the duty length of node S in the network is τ, and the size of the forwarding set of node S is N. In the process of data transmission, node S selects n nodes from N forwarding nodes as relay. We refer to the ith waking node in the forwarding set as the N_i node, where $i = 1, 2, \ldots, N$.According to the order of waking, the node that keeps listening is called the n_i node, where $i = 1, 2, \ldots, n$. We divide each clock cycle equally into τ, each called a slot. In order, we call these slots $slot_i$, where $i = 0, 1, \ldots, (\tau - 1)$.The duty cycle equal to $1/\tau$ means that the node wakes up for 1 slot in one clock cycle, and sleeps at other times.

B. ANALYSIS OF THE UNIQUE PERFORMANCE IN THE MOR SCHEME

In the Modified Opportunistic Routing (MOR) scheme, the sensor node wakes up randomly throughout the clock cycle. Therefore, it is highly probable that no n candidate nodes are in the awake state at the same time. Therefore, we made the following improvements to the duty cycle control in the MOR scheme. First, once the forwarding node wakes up, it is first determined whether the number of nodes in the awake state reaches n. If not, the node will remain awake until the data transfer is complete. Otherwise, go to sleep to save energy.

Since the node wakes up randomly throughout the entire cycle, the node wakes up with the possibility of $1/\tau$ in each slot. If the node wakes up in $slot_k$, it means that the node does not wake up in the previous slot:

$$P_k^{\text{one}} = (1-\frac{1}{\tau})^k \frac{1}{\tau} \tag{63}$$

Where $k = 0, 1, \ldots, (\tau - 2)$.

In particular, the node must wake up once in one clock cycle. If the node does not wake up in the first $(\tau - 2)$ slots, then it must wake up in $slot_{\tau-1}$:

$$P_{\tau-1}^{\text{one}} = (1-\frac{1}{\tau})^{\tau-1} \tag{64}$$

Then, as of $slot_k$, the probability that the node has woken up is:

$$P_{uk}^{one} = \sum_{i=0}^{k} P_i^{\text{one}} \tag{65}$$

Where $k = 0, 1, \ldots, (\tau - 1)$.

Suppose that the N_n candidate node wakes up at $slot_0$, that is, at least n candidate nodes wake up at $slot_0$, so the corresponding probability is:

$$P_0^n = 1 - \sum_{m=0}^{n-1} C_N^m P_{u0}^{one^m} \left(1 - P_{u0}^{one}\right)^{N-m} \tag{66}$$

Where C_N^m indicates that m nodes are randomly selected from N nodes; $P_{u0}^{one^m}$ indicates that the selected m nodes wake up at $slot_0$, and the remaining $N - m$ nodes are not awake, denoted by $\left(1 - P_{u0}^{one}\right)^{N-m}$.

$$C_N^m = \frac{N!}{(N-m)!m!} \tag{67}$$

If the N_n candidate node wakes up at $slot_{\tau-1}$, it means that in the previous slot, at most $n - 1$ nodes wake up. The corresponding probability is:

$$P_{\tau-1}^n = \sum_{m=0}^{n-1} C_N^m P_{u(\tau-2)}^{one^m} \left(1 - P_{u(\tau-2)}^{one}\right)^{N-m} \tag{68}$$

If the N_n node wakes up in some other $slot_k$, then at most $n - 1$ nodes wake up in the first $k - 1$ slots.

We suppose that m nodes wake up in the first $k - 1$ slots, then at least $n - m$ nodes wake up at $slot_k$, the corresponding probability is:

$$P_k^n = \sum_{m=0}^{n-1} \left(C_N^m P_{u(k-2)}^{one\ m} A\right)$$

$$A = \sum_{j=n-m}^{N-m} C_{N-m}^j P_k^{\text{one}^j} \left(1 - P_{u(k-2)}^{one}\right)^{N-m-j} \tag{69}$$

The sender node is also a sensor node in the network that wakes up in the same way as other nodes in the network. If sender node S has woken up when N_n candidate node wakes up, the one-hop delay is the time when the N_n candidate node wakes up. Conversely, when the N_n candidate node wakes up, node S has not awake, and the one-hop delay is the time when node S wakes up. In particular, if the N_n node wakes up at $slot_{\tau-1}$, node S must have woken up.

In summary, the one-hop delay of node S can be expressed as:

$$D_s = \sum_{k=0}^{\tau-2} \left(k * P_k^n * P_{uk}^{\text{S}} + \sum_{i=k+1}^{t-1} i * P_k^n * P_i^{\text{S}} \right) + (\tau - 1) * P_{\tau-1}^n \tag{70}$$

Where $P_{uk}^{\text{S}} = P_{uk}^{\text{one}}$, indicating the probability that the node S has awake as of $slot_k$; $P_i^{\text{S}} = P_i^{\text{one}}$, indicating the probability that the node S wakes up at $slot_i$.

If the node is located on the ring closest to the sink, then once the node wakes up, data can be transferred (sink is always in the awake state), and the delay of the node is:

$$D_S^0 = \sum_{k=0}^{\tau-2} \left(k * P_k^{\text{one}}\right) + (\tau - 1) * P_{\tau-1}^{\text{one}} \tag{71}$$

When the node's duty length is the same ($\tau = 20$), and the number of forwarding nodes and the number of candidate nodes are different, the one-hop delay is as shown in Fig. 19.

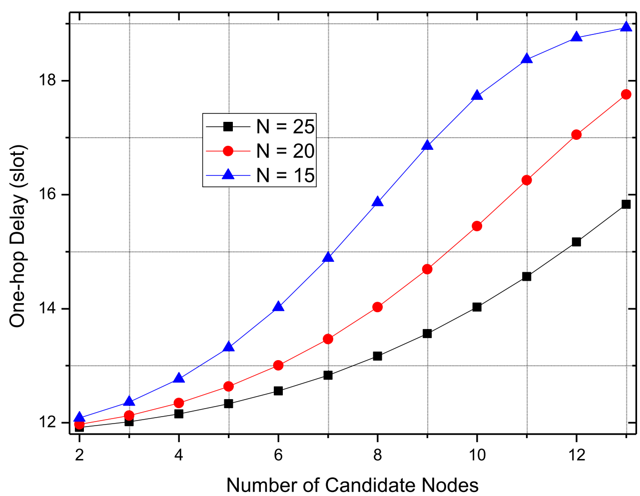

FIGURE 19. One-hop delay of the node when $\tau = 20$ (I).

Since the node's duty length is the same, the probability that the node wakes up in each slot is the same. When the number of forwarding nodes is the same, the more the number of candidate nodes, the longer it takes to wait for these candidate nodes to wake up, and the one-hop delay is larger. When the number of candidate nodes is the same, the more nodes in the forwarding set, the shorter the waiting time for n nodes to wake up, and the one-hop delay is smaller.

When the number of candidate nodes is constant ($n = 3$), and the duty length and forwarding nodes are different, the one-hop delay of the node is as shown in Fig. 20. When the number of nodes in the forwarding set is the same, the probability that the node with a larger duty length wakes

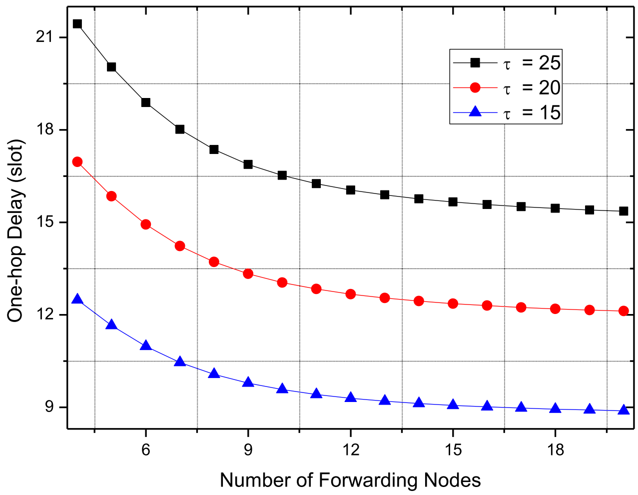

FIGURE 20. **One-hop delay of the node when $\tau = 20$ (II).**

up in each slot is smaller, waiting for the n nodes to wake up for a longer time, and waiting for the node S to wake up for a longer time. Correspondingly, the delay of the node is larger.

When the number of nodes in the forwarding set is the same ($N = 20$), the one-hop delay of the node when the duty length and the number of candidate nodes are different are shown in Fig. 21. When the number of candidate nodes is the same, the larger the duty length, the lower the probability that the node wakes up in a single slot, and the longer it takes to wait until the n_n candidate node and node S wake up, and the one-hop delay is larger.

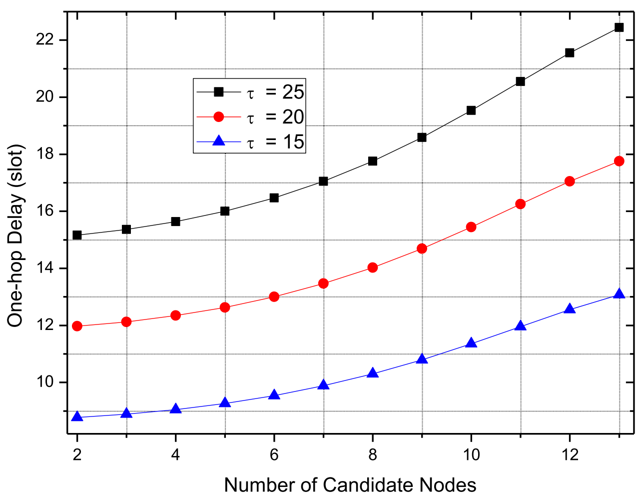

FIGURE 21. **One-hop delay of the node when $\tau = 20$ (III).**

We have analyzed the delay of the nodes in the MOR scheme. Below we continue to explore the time that the nodes remain Low Power Listening (LPL). When the N_n node wakes up at $slot_k$, the first $n-1$ candidate nodes have already woken up at $slot_i$, where $i = 0, 1, \ldots, k$. Then the average listening time of one of the first $n-1$ candidate nodes is:

$$T_1^{uk} = \sum_{i=0}^{k} \frac{P_i^{one}}{P_{uk}^{one}} \text{ (k-i)} \tag{72}$$

So when the N_n node wakes up (the listening time of the N_n node is 0), the average listening time of the n candidate nodes is:

$$\begin{aligned} T_n^{uk} &= \frac{(n-1)\, T_1^{uk} + 0}{n} \\ &= \frac{n-1}{n} \sum_{i=0}^{k} \frac{P_i^{one} \text{ (k-i)}}{P_{uk}^{one}} \end{aligned} \tag{73}$$

When the node S wakes up before the N_n node wakes up or wakes up with the N_n node, the average listening time of the node is the average listening time until the N_n node wakes up. When node S wakes up after the N_n node wakes up, this means that after n nodes wake up, they need to wait for node S to wake up.

Therefore, when the N_n node wakes up at $slot_k$, the average time that the n candidate nodes remain listening is:

$$T_k^n = T_n^{uk} * P_k^n * P_{uk}^{S} + \sum_{i=k+1}^{\tau-1} \left(T_n^{uk} + i - k\right) * P_k^n * P_i^{S} \tag{74}$$

Since then, we have considered the listening time of the first n nodes. Below we continue to discuss the listening time of other $N - n$ nodes. When these nodes wake up, they will send an ACK packet to node S. If node S wakes up, it will immediately respond to an ACK packet to put it to sleep. The time that the node keeps listening is equal to the time when two ACK packets are transmitted. If node S does not wake up, then it is necessary to wait until node S wakes up before returning an ACK packet to put it to sleep. At this point, the node keeps listening for a time equal to the time that node S wakes up minus the time itself wakes up, plus the time to transmit an ACK packet. Let us suppose that the N_n node wakes up at $slot_k$, then the remaining $N-n$ nodes wake up in a slot from $slot_k$ to $slot_{\tau-1}$.The probability that a single node wakes up at $slot_k$ or after $slot_k$ is:

$$1 - P_{u(k-1)}^{one} \tag{75}$$

Therefore, the probability that a single node wakes up at $slot_i$ (on the premise that the N_n node wakes up at $slot_k$, and $i \geq k$) is:

$$\sum_{j=0}^{i} P_j^n \frac{P_i^{one}}{1 - P_{u(j-1)}^{one}} \tag{76}$$

In particular, when $j = 0$, $1 - P_{u(j-1)}^{one} = 1$. The probability that node S has woken up at $slot_i$ is:

$$\sum_{j=0}^{i} P_j^{\text{one}} = P_{ui}^{\text{one}} \tag{77}$$

The probability of not waking up is:

$$1-\sum_{k=0}^{i} P_j^{\text{one}} \tag{78}$$

When the node S does not wake up at $slot_i$, the probability that the node wakes up at $slot_j$ is ($i < j$):

$$P_j^S = \sum_{j=\mathrm{i}+1}^{\tau-1} \frac{P_{uj}^{one}}{1-P_{ui}^{one}} \tag{79}$$

Therefore, the average time for one of the N-n nodes to keep listening when waking up at $slot_i$ is:

$$T_i^{N-n} = \left(\sum_{j=0}^{i} P_j^n \frac{P_i^{one}}{1-P_{u(j-1)}^{one}}\right) \times \left\{P_{ui}^{\text{one}} \cdot 2t + \left(1-P_{ui}^{\text{one}}\right)\left[P_j^S\left(t+j-i\right)\right]\right\} \tag{80}$$

Where t represents the time at which the node transmitted an ACK packet. In the energy consumption model introduced in section III.C, the ACK packet size is $8bytes$ and the data transmission rate is $19.2kbps$. Therefore, $t = 3.33 \times 10^{-3}s$. It should be noted that all time except t is in slot units. When calculating the specific value, we need to unify the unit first.

In summary, the average listening time of nodes in the MOR scheme is:

$$T_{LPL} = \frac{n}{N}\sum_{k=0}^{\tau-1} T_k^n + \frac{N-n}{N}\sum_{\mathrm{i}=0}^{\tau-1} T_i^{N-n} \tag{81}$$

The power when the node remains in the listening state is P_{LPL}, and the energy consumed by the node in the LPL during a data transmission is:

$$E_{LPL} = \frac{n}{N}P_{LPL}\sum_{k=0}^{\tau-1} T_k^n + \frac{N-n}{N}P_{LPL}\sum_{\mathrm{i}=0}^{\tau-1} T_i^{N-n} \tag{82}$$

When the node's duty length is the same ($\tau = 20$), and the number of forwarding nodes and the number of candidate nodes are different, the energy consumption of the node due to LPL is shown in Fig. 22.

When the number of candidate nodes is small, the more nodes in the forwarding set, the more energy is consumed. When the number of candidate nodes is large, the more nodes in the forwarding set, the smaller the energy consumed.

When the number of candidate nodes of the node is unchanged ($n = 3$), and the number of duty length and forwarding nodes are different, the energy consumption of the node due to LPL is shown in Fig. 23.

When the number of nodes in the forwarding set is the same, the larger the duty length, the lower the probability that the node will wake up in a single slot. Therefore, the later the time when the N_n candidate node and the node S wake up, the longer the candidate node keeps listening, and the more energy is consumed.

When the number of nodes in the forwarding set of the node is the same ($N = 20$), and the duty length and the number of candidate nodes are different, the energy consumption of the node due to the listening is as shown in Fig. 24.

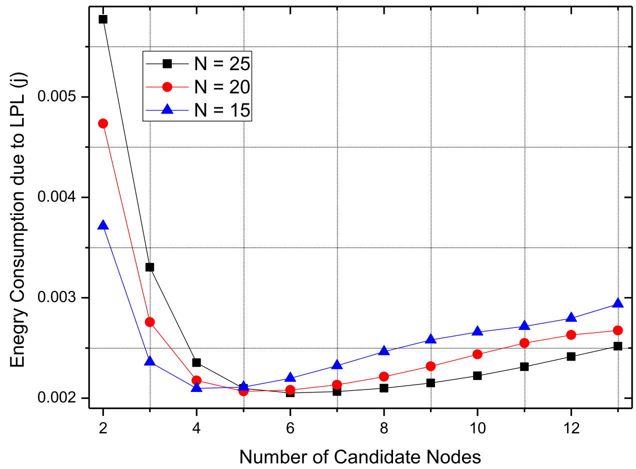

FIGURE 22. **Energy consumption due to LPL when $\tau = 20$ (I).**

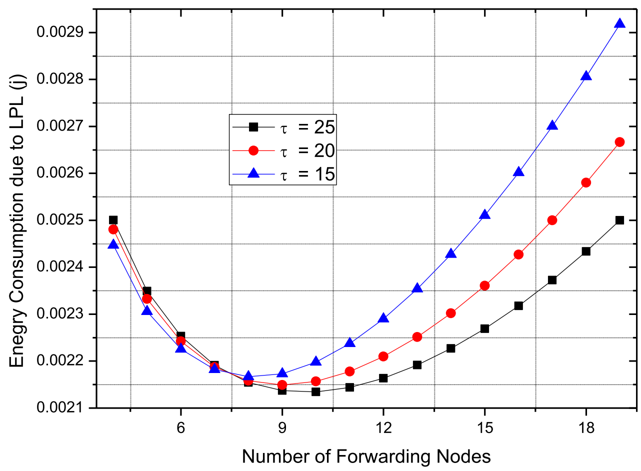

FIGURE 23. **Energy consumption due to LPL when $\tau = 20$ (II).**

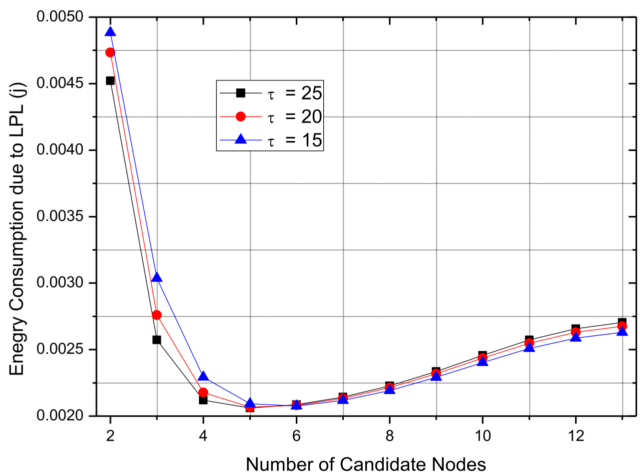

FIGURE 24. **Energy consumption due to LPL when $\tau = 20$ (III).**

In section V.A, we calculated the number of ACK packets sent by the node in the OR scheme during a round of data transmission. In the MOR scheme, we need to use the following method to calculate the number of ACK packets.

According to the previous analysis, there are Q_i nodes on the $ring_i$, and these nodes will be the forwarding nodes of the nodes on the $ring_{i+1}$. There are a total of Q_{i+1} nodes on the $ring_{i+1}$, and each node sends Q_{i+1}^S packets, and each node needs N nodes as forwarding nodes. Therefore, in a round of data transmission, the number of times the node on the $ring_i$ acts as a forwarding node is:

$$N_i Q_{i+1}^S \frac{Q_{i+1}}{Q_i} \tag{83}$$

We suppose that node A is the forwarding node of node B, located on the $ring_i$ and the $ring_{i+1}$, respectively. If node A wakes up, it does not receive an ACK packet from node B that causes it to go to sleep. This means that either node B has not woken up, or node B has woken up, but the number of candidate nodes of node B has not reached n. At this point, node A directly sends an ACK packet to node B, telling that it has woken up, otherwise, goes directly to sleep.

Let's suppose that the time that node A wakes up is $slot_k$. At this time, the probability that node B has already woken up is P_{uk}^{one}, and the probability of not waking up is $1 - P_{uk}^{\text{one}}$. Node A sends an ACK packet. If Node B is already awake, but the number of candidate nodes waking up has not exceeded n (including node A), node B will also send an ACK packet to node A. The probability at this time is:

$$P_{uk}^{\text{one}} \sum_{j=k}^{\tau-1} P_j^n \tag{84}$$

Therefore, the number of ACK packets sent by the node to the previous hop node in the MOR scheme is:

$$N_i Q_{i+1}^S \frac{Q_{i+1}}{Q_i} \cdot \sum_{k=0}^{\tau-1} \left[\left(1 - P_{uk}^{\text{one}}\right) + P_{uk}^{\text{one}} \sum_{j=k}^{\tau-1} P_j^n \right] \tag{85}$$

When node A is the sender, it will also receive N ACK packets from the $ring_{i-1}$, and it needs to respond in the order of arrival of these packets. (Our default packet receiving order is the same as the sending order. If there are multiple packets arriving at the same time, then these packets can be randomly numbered). For the forwarding nodes corresponding to the first n ACK packets, the data packet is directly sent as a response, and for other forwarding nodes, the ACK packet is sent to inform the nodes to enter a sleep state.In summary, the number of ACK packets sent by the node on the $ring_i$ in the MOR scheme is:

$$Q_i^{ACK-MOR} = Q_i^R \frac{P_i}{n_i p_i} + (N_i - n_i) + N_i Q_{i+1}^S \frac{Q_{i+1}}{Q_i} \cdot \sum_{k=0}^{\tau-1} \left[\left(1 - P_{uk}^{\text{one}}\right) + P_{uk}^{\text{one}} \sum_{j=k}^{\tau-1} P_j^n \right] \tag{86}$$

C. ANALYSIS OF THE UNIQUE PERFORMANCE IN THE ASUD SCHEME

In the Active Slot Uniform Distribution (ASUD) scheme, the nodes in the forwarding set of the node S wake up uniformly in the clock cycle, and the node S only needs n candidate nodes to perform data transmission with high reception rate.

If node S wakes up later, there may already be more than n candidate nodes waking up and keeping listening, consuming unnecessary energy. In response to this situation, we make special regulations. After node n wakes up, if another node wakes up, let the node with the longest listening time go to sleep state, reducing energy consumption.

Since N nodes wake up evenly in the duty length, then every τ/N slots, there will be a candidate node waking up. Therefore, the node N_n wakes up at $(n-1)\,\tau/N$ slot and the one-hop delay is $(n-1)\,\tau/N$ slot as long as the node S wakes up before or at $(n-1)\,\tau/N$.

If node S wakes up after node N_n wakes up, since the number of nodes that remain listening is always n, when a new node wakes up, the previous node in the listening state will go to sleep. This is equivalent to starting from the beginning of the clock cycle, waking up n nodes in turn and keeping the state of listening. Once node S wakes up, it immediately stops listening and transmits data packets.

$$D^S = (n-1)\frac{\tau}{N} \sum_{i=0}^{\lfloor (n-1)\frac{\tau}{N} \rfloor} P_i^s \tag{87}$$

In particular, on the ring that is closest to sink, the delay of the node is (the reason is the same as in the MOR scheme, and will not be described again):

$$D_S^0 = \sum_{i=\lfloor (n-1)\frac{\tau}{N} \rfloor + 1}^{\tau-1} i * P_i^s + \sum_{k=0}^{\tau-2} \left(k * P_k^{\text{one}}\right) + (\tau - 1) * P_{\tau-1}^{\text{one}} \tag{88}$$

When the duty length of the node is the same ($\tau = 20$), and the number of forwarding nodes and the number of candidate nodes are different, the one-hop delay of the node is as shown in Fig. 25.

When the number of nodes in the forwarding set is the same, the more candidate nodes, the more time is needed to wake up the N_n candidate node, so the one-hop delay is larger. When the number of candidate nodes is the same, the more nodes in the forwarding set, the shorter the waiting time for the N_n candidate node to wake up, and the smaller the one-hop delay.

When the number of candidate nodes of the node is unchanged ($n = 3$), and the number of duty length and forwarding nodes are different, the delay of the node is as shown in Fig. 26. When the number of nodes in the forwarding set is the same, the larger the duty length, the smaller the probability that a single node wakes up in a slot. Thus, the longer the waiting time for the N_n candidate node to wake up, the greater the one-hop delay.

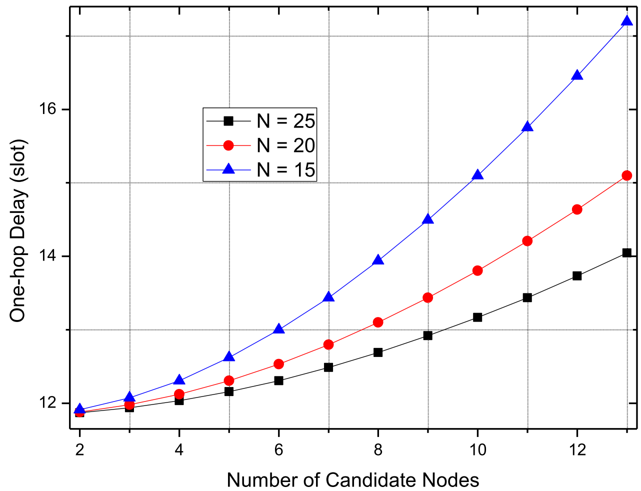

FIGURE 25. **One-hop delay of the node when $\tau = 20$ (IV).**

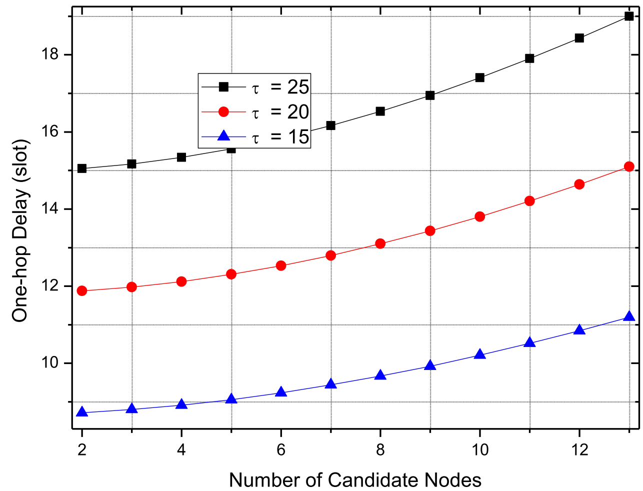

FIGURE 27. **One-hop delay of the node when $\tau = 20$ (VI).**

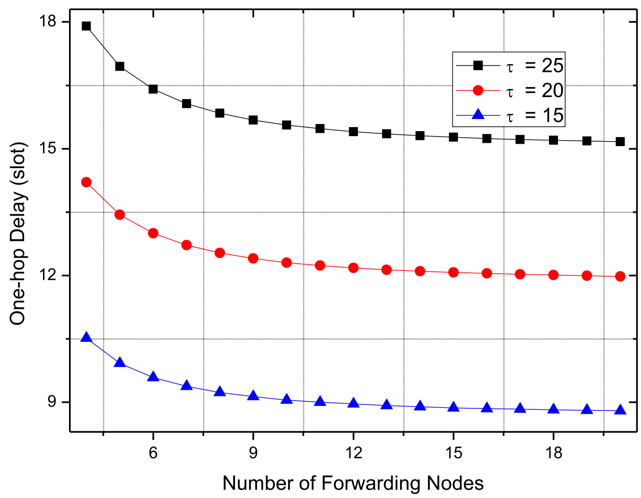

FIGURE 26. **One-hop delay of the node when $\tau = 20$ (V).**

When the number of nodes in the forwarding set is the same ($N = 20$), and the duty length and the number of candidate nodes are different, the delay of the single hop is as shown in Fig. 27. When the number of candidate nodes of a node is the same, the greater the duty length of the node, the smaller the probability that the node wakes up in a slot. Thus, the longer the waiting time for the node S and the N_n candidate node to wake up, the greater the one-hop delay.

Suppose node S wakes up at $slot_k$. If $k < \lfloor (n-1)\,\tau/N \rfloor$, it means that the number of nodes waking up has not reached threshold n. At this time, the listening time is the difference between the time when the node N_n wakes up and the time when the node S wakes up. On the other hand, if $k \geq \lfloor (n-1)\,\tau/N \rfloor$, it means that the node S wakes up at the same time or after the node N_n wakes up. Since n nodes are always in the listening state, the listening time is the time difference between the wake-up time of the node S and the wake-up time of the candidate node.

When the node S wakes up before the N_n candidate node wakes up, since the N nodes wake up uniformly during the τ slots, the time when the N_i nodes wake up is $\lfloor (i-1)\,\tau/N \rfloor$. Therefore, when node N_n wakes up, the time that the node N_i keeps listening is equal to the time that the node N_n wakes up $\lfloor (n-1)\,\tau/N \rfloor$ minus the time when the node N_i wakes up $\lfloor (i-1)\,\tau/N \rfloor$. Therefore, the average time that the first n nodes remain listening is:

$$T_n^{u(n-1)} = \frac{1}{n}\sum_{i=1}^{n}\left(\lfloor (n-1)\,\tau/N \rfloor - \lfloor (i-1)\,\tau/N \rfloor\right) \quad (89)$$

Node S wakes up after the N_n candidate node wakes up. Once a new node wakes up, at the same time there will be a wake-up node going to sleep (automatically controlled by time). Therefore, we can suppose that the first n nodes are always listening until node S wakes up.

Therefore, the average time that nodes in the ASUD scheme remain listening is:

$$\begin{aligned} T_{average}^n = &\sum_{i=0}^{\lfloor (n-1)\frac{\tau}{N} \rfloor} P_i^s T_n^{u(n-1)} \\ &+ \sum_{i=\lfloor (n-1)\frac{\tau}{N} \rfloor+1}^{\tau-1} P_i^s \left(T_n^{u(n-1)} + i - n + 1\right) \end{aligned} \quad (90)$$

The energy consumed is:

$$E^{LPL} = P_{LPL}\frac{n}{N}T_{average}^n \quad (91)$$

In particular, on the ring closest to the sink, the node sends a packet to the sink as soon as it wakes up (the listening time is 0), and the energy consumed is 0.

When the duty length of the node is the same ($\tau = 20$), and the number of forwarding nodes and the number of candidate nodes are different, the energy consumption of the node due to the listening is as shown in Fig. 28.

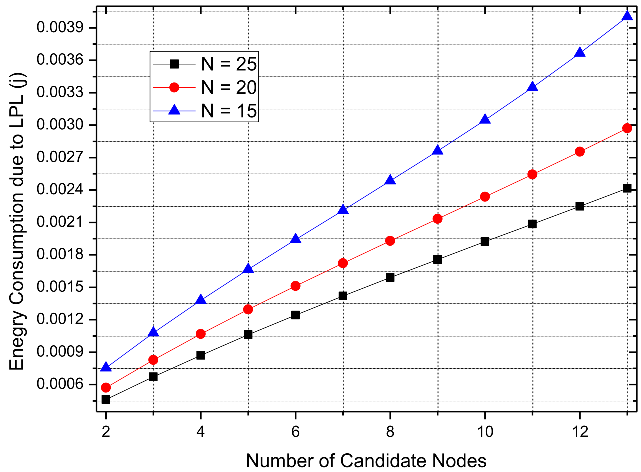

FIGURE 28. Energy consumption due to LPL when $\tau = 20$ (IV).

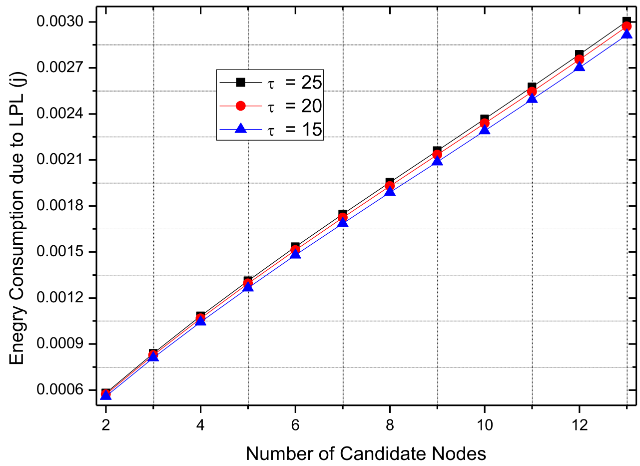

FIGURE 30. Energy consumption due to LPL when $\tau = 20$ (VI).

When the size of the forwarding set of the node is the same, the more candidate nodes, the longer the waiting time for the candidate nodes to wake up, and the longer the nodes keeps listening. When the number of candidate nodes of the node is the same, the more nodes in the forwarding set, and the shorter the listening time.

When the number of candidate nodes of the node is unchanged ($n = 3$), and the duty length and the number of forwarding nodes are different, the energy consumption of the node due to the listening is shown in Fig. 29.

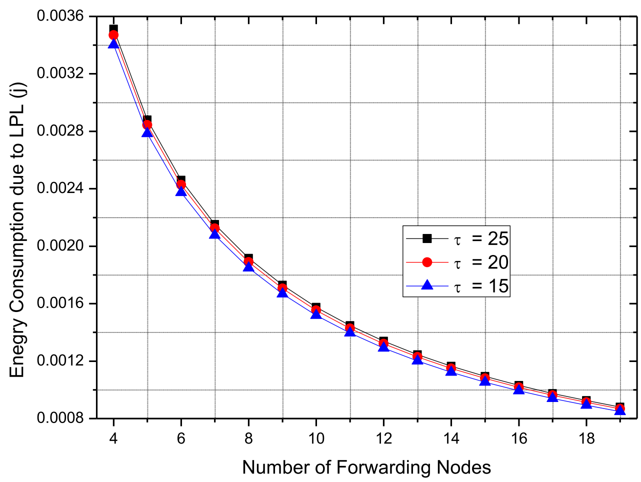

FIGURE 29. Energy consumption due to LPL when $\tau = 20$ (V).

When the number of nodes in the forwarding set is the same, the greater the duty cycle of the node, the smaller the probability that the node wakes up in a slot. Thus, the longer the waiting time for the N_n candidate node to wake up, the longer the node remains listening, and the greater the energy consumed by the node.

When the number of nodes in the forwarding set is the same ($N = 20$), and the duty length and the number of candidate nodes are different, the energy consumption of the node due to the listening is shown in Fig. 30. When the number of candidate nodes is the same, the greater the duty length of the node, the lower the probability that the node wakes up in a slot. Thus, the longer the waiting time for the N_n candidate node to wake up, the longer the time to keep listening, and the greater the energy consumed.

In the ASUD scheme, there are two cases of ACK packets sent by a node.

In the first round of data transmission, the nodes in the network are still unclear about their wake-up time (in a state of random wake-up). From the second round of data transmission, the node will wake up according to a certain rule. Therefore, in the first round of data transmission, node S must set the initial value of the wake-up time of the node in the forwarding set. When node S acts as the receiver, whenever the node wakes up, it needs to send an ACK packet to inform the sender that it has woken up. When node S acts as the sender, it also needs to respond to the ACK packet to the forwarding nodes to tell them when to wake up.

The total number of ACK packets sent by the node is:

$$N_i Q_{i+1}^S \frac{Q_{i+1}}{Q_i} \cdot + Q_i^R \frac{P_i}{n_i p_i} + N_i \tag{92}$$

The number of ACK packets sent by the node on the $ring_i$ in the ASUD scheme (first round):

$$Q_i^{ACK-ASUD-I} = Q_i^R \frac{P_i}{n_i p_i} + N_i + N_i Q_{i+1}^S \left\{ 1 + \frac{2r}{2\mathrm{R} + \mathrm{r}\,[2\,(\mathrm{i\text{-}m}) + 1]} \right\} \tag{93}$$

When the packet transmission proceeds to the second round, the nodes in the ASUD scheme wake up uniformly in the duty length. These nodes wake up and listen for a while, then go to sleep (the number of nodes that keep waking up is no more than n). The node does not need to send an ACK packet to inform the sender that the node itself has woken up, because the sender node can judge which nodes are in the awake state by time. If the sender completes the data transfer in a certain slot, in order to save energy, it will send an ACK packet to the node that has not woken up in the forwarding set. Once these nodes wake up and receive this ACK packet, they will go straight to sleep. Suppose node S wakes up as a sender at $slot_k$. The N_n candidate node wakes up at $(n-1)\,\tau/N$ slot. If $k < (n-1)\,\tau/N$, since the number of candidate nodes of node S has not reached n, ACK packets will not be sent. When $k \geq (n-1)\,\tau/N$, the number of candidate nodes of node S has reached n. At this point, it will send ACK packets to those nodes that have not yet woken up so that they do not need to listen, but go directly to sleep. By the $slot_k$, the number of nodes that have been woken up in the forwarding set is $\lceil kN/\tau \rceil$, and the number of nodes that are not awake is $N - \lceil kN/\tau \rceil$.

In summary, in the following transmission rounds, the number of ACK packets sent by the node on the $ring_i$ in the ASUD scheme is:

$$Q_i^{ACK-ASUD-1} = Q_i^R \frac{P_i}{n_i p_i} + \sum_{k=\lceil (n_i-1)\tau/N \rceil}^{\tau-1} P_k^{\text{one}} \left(N_i - \lceil kN_i/\tau \rceil\right) \tag{94}$$

D. ANALYSIS OF THE UNIQUE PERFORMANCE IN THE ASG SCHEME

In the Active slot group (ASG) scheme, we group all the forwarding nodes per n nodes and let these groups wake up evenly in the duty length. When grouping N nodes, we can divide them into x groups:

$$x = \lceil \frac{N}{n} \rceil \tag{95}$$

We call the ith group as $group_i$, and:

$$m = nx - N \tag{96}$$

Where m is any non-negative integer less than n. When m is equal to 0, it means that N nodes can be divided into x groups, which is the most ideal situation. In the actual situation, the probability that N nodes cannot be evenly distributed is greater.

In this case, we take m out of $n(x-1)$ nodes that have been successfully grouped before, and $n-m$ nodes that are not grouped, and make them into the last group. Specifically, we first number the N nodes in the order in which the nodes wake up during the first round of data transmission, which are $0, 1, 2, \ldots, N-1$, respectively. Each time the node wakes up, the number of all nodes is decremented by n. If the value obtained is not less than zero, the node remains in sleep state. Conversely, the node is awakened and the node's sequence number is incremented by N. Therefore, the probability that each node wakes up once or twice in a duty length is the same.

After the grouping is completed, the node will wake up evenly throughout the duty length in groups, that is, the node in the $group_i$ wakes up at $i\tau/x$ slot.

When $x > \tau$, there will be more than n nodes waking up in a certain slot. However, the node S only needs n candidate nodes to perform data transmission with higher reception rate. Therefore, we can control τ groups to wake up and $x-\tau$ groups do not. We first label all the groups, which are $1, 2, \ldots, x$. Whenever a packet should wake up, the label of all packets is decremented by 1. If the result is greater than zero, then the nodes in this group remains asleep; otherwise, it means that the nodes in the group needs to wake up immediately. At the same time, the label of this group is changed to x.

When $x/\tau \geq 1$, τ groups just occupy the length of the entire duty length and there is no overlap between them. Suppose node S wakes up at $slot_i$, then before that, there are exactly i groups waking up and going to sleep after listening to one slot, so the average one-hop delay of the node is:

$$D^S_{\frac{x}{\tau}\geq 1} = \frac{n}{N}\sum_{i=0}^{\tau-1} i*P_i^s \tag{97}$$

When $N/\tau < 1$, if node S wakes up at $slot_i$, either n nodes are awake to directly transmit packets, or none of the candidate nodes are awake. Node S needs to wait until the n candidate nodes of the next group wake up to transmit data. In particular, if the node S is still not awake when the candidate nodes of the last group are woken up, then the nodes in the last group will remain in the listening state until the node S wakes up and completes the data transmission.

Suppose node S wakes up at $slot_i$. At this point, the number of groups that have waking up is $\lceil ix/\tau \rceil$. When $(\lceil ix/\tau \rceil - 1)(\tau/x) + 1 > i$, it means that n nodes in the $group_{\lceil ix/\tau \rceil}$ have not entered the sleep state. At this point, the one-hop delay of the single hop is the time when the node S wakes up:

$$D^S_{\frac{x}{\tau}<1} = \frac{n}{N}\sum_{i=0}^{\tau-1} iP_i^s \tag{98}$$

Conversely, the n nodes in the $group_{\lceil ix/\tau \rceil}$ have theoretically gone to sleep, but there are actually two cases: If $\lceil ix/\tau \rceil = x$, this means that it is already the last group. Since the node S must perform data transmission in this round, the last group must wait until the node S wakes up to transmit the data and then goes to sleep, and the one-hop delay is the time when the node S wakes up. Otherwise, there are still other candidate nodes waking up after this group, and the one-hop delay is the time when the next group of nodes wakes up. In summary, the one-hop delay of the node is:

$$D^S_{\frac{x}{\tau}<1} = \frac{n}{N}\sum_{i=0}^{\tau-1} aP_i^s \tag{99}$$

When $\lceil ix/\tau \rceil = x$, $a = i$; otherwise, $a = \lceil ix/\tau \rceil \tau$/x.

In particular, on the ring that is closest to sink, the one-hop delay of the node is:

$$D_S^0 = \sum_{k=0}^{\tau-2}\left(k * P_k^{\text{one}}\right) + (\tau - 1) * P_{\tau-1}^{\text{one}} \tag{100}$$

The reason is the same as in the MOR scheme, and will not be described again.

When the node's duty length is the same ($\tau = 20$), and the number of forwarding nodes and candidate nodes are different, the one-hop delay of the node is as shown in Fig. 31. When the number of candidate nodes of the node is the same, the more the number of forwarding nodes, the shorter the waiting time for the n candidate nodes to wake up, and the smaller the one-hop delay. When the number of nodes in the forwarding set is the same, the more the number of candidate nodes, and the longer the waiting time for the n candidate nodes to wake up, the greater the one-hop delay.

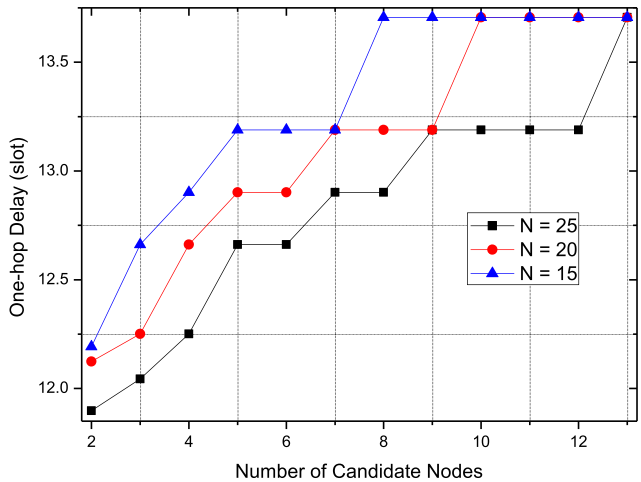

FIGURE 31. One-hop delay of the node when $\tau = 20$ (VII).

When the number of candidate nodes is constant ($n = 3$), and the value of duty length and the number of forwarding nodes are different, the one-hop delay of the node is as shown in Fig. 32.

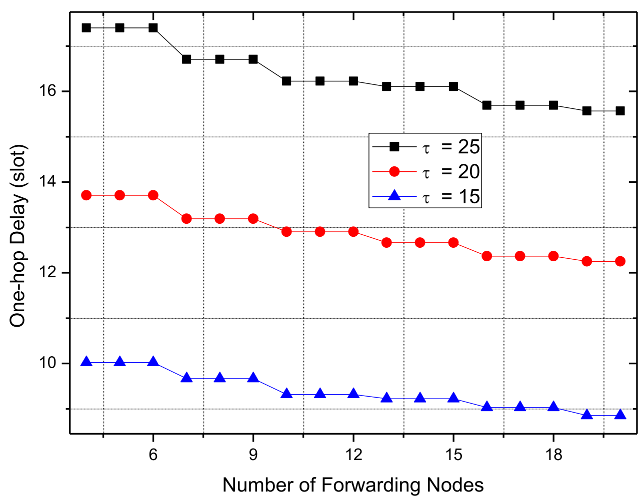

FIGURE 32. One-hop delay of the node when $\tau = 20$ (VIII).

When the number of forwarding nodes is the same, the greater the duty length of the node, the smaller the probability that the node wakes up in each slot, and the longer the waiting time for the n candidate nodes to wake up, the larger the one-hop delay.

When the number of nodes in the forwarding set of a node is the same ($N = 20$), and the duty length and the number of candidate nodes are different, the delay of the single hop of the node is as shown in Fig. 33.

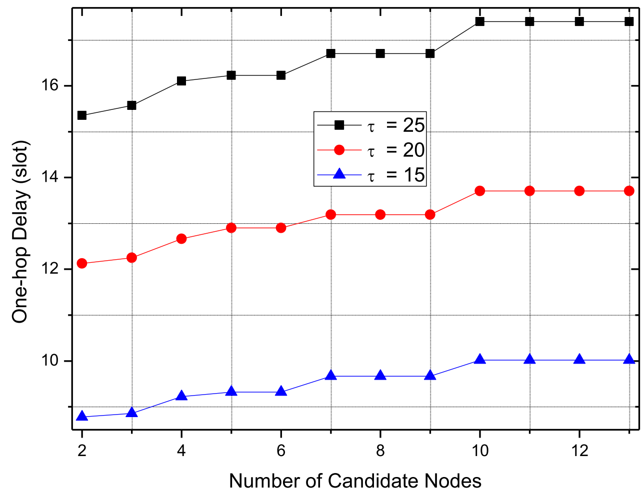

FIGURE 33. One-hop delay of the node when $\tau = 20$ (IX).

When the number of candidate nodes is the same, the greater the duty length of the node, the smaller the probability that the node wakes up in a slot, and the longer the waiting time for the n candidate nodes to wake up, the larger the one-hop delay.

As before, our classification discusses the energy consumed by the nodes while they are listening.

When $x/\tau \geq 1$, the data transmission can be carried out immediately when the node S wakes up. While each group goes to sleep, the next group will wake up immediately. This means that the time the node listens can be represented by the time that the first group wakes up to the time interval that the node S wakes up, so the average listening time of the node is:

$$T_{N/\tau \geq 1}^{LPL} = \frac{n}{N} \sum_{i=0}^{\tau-1} P_i^s i \tag{101}$$

The energy consumed by the node because of LPL is:

$$E_{N/\tau \geq 1}^{LPL} = P_{LPL} T_{N/\tau \geq 1}^{LPL} \tag{102}$$

Which is:

$$E_{N/\tau \geq 1}^{LPL} = P_{LPL} \frac{n}{N} \sum_{i=0}^{\tau-1} P_i^s i \tag{103}$$

When $x//\tau < 1$, suppose that node S wakes up at $slot_i$, and the number of groups that have been awake at this time is $\lceil ix/\tau \rceil$.

When $(\lceil ix/\tau \rceil - 1)(\tau/x) + 1 \geq i$, it means that n nodes in the $group_{\lceil ix/\tau \rceil}$ have not yet entered the sleep state.

At this point, the nodes in the first $\lceil ix/\tau \rceil - 1$ groups have already listened to a slot.

The listening time of the nodes in the $group_{\lceil ix/\tau \rceil}$ is less than one slot, so the average time that the node keeps listening is:

$$T^{LPL}_{\frac{x}{\tau}<1} = \frac{n}{N} \sum_{i=0}^{\tau-1} P_i^s \left\{ \begin{array}{c} \left(\left\lceil \frac{ix}{\tau} \right\rceil - 1 \right) \\ + \left[i - \left(\left\lceil \frac{ix}{\tau} \right\rceil - 1 \right) \frac{\tau}{x} \right] \end{array} \right\} \tag{104}$$

Conversely, the n nodes in the $group_{\lceil ix/\tau \rceil}$ go to sleep, and there are two cases.

If the $group_{\lceil ix/\tau \rceil}$ is not the last group, then the nodes in the $group_{\lceil ix/\tau \rceil}$ can safely go to sleep after listening to a slot. At this time, the time that the node keeps listening is equal to the sum of the time that the previous $\lceil ix/\tau \rceil$ groups remain listening (one slot).

If the $group_{\lceil ix/\tau \rceil}$ is the last group, then after 1 slot, the nodes in the group cannot enter the sleep state, but wait until the node S wakes up and complete the data transmission. At this time, the delay is the time that the previous $\lceil ix/\tau \rceil - 1$ groups keep listening (one slot), plus the time of the last group listening (less than 1 slot). Therefore, the average time that a node remains listening is:

$$T^{LPL}_{\frac{x}{\tau}<1} = \frac{n}{N} \sum_{i=0}^{\tau-1} P_i^s a \tag{105}$$

If $\lceil ix/\tau \rceil = x$, then $a = (\lceil ix/\tau \rceil - 1) + [i - (\lceil ix/\tau \rceil - 1)(\tau/x)]$; otherwise, $a = \lceil ix/\tau \rceil$.

When the node's duty length is the same ($\tau = 20$), and the number of forwarding nodes and the number of candidate nodes are different, the energy consumption of the node due to the listening is shown in Fig. 34.

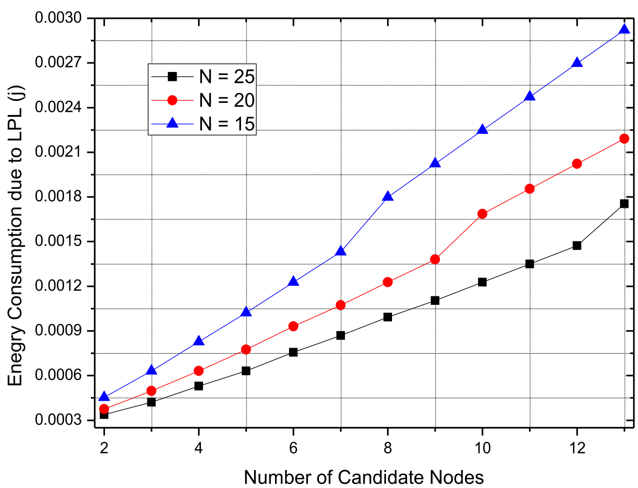

FIGURE 34. Energy consumption due to LPL when $\tau = 20$ (VII).

When the number of candidate nodes is the same, the larger the number of nodes in the forwarding set of the node, the shorter the time that the node keeps listening, the smaller the energy consumed by the node.

When the number of candidate nodes of the node is unchanged ($n = 3$), and the number of duty length and forwarding nodes are different, the energy consumption of the node due to the listening is shown in Fig. 35. When the number of forwarding nodes of the node is the same, the greater the duty length of the node, the smaller the probability that the node wakes up in a slot, the longer the node keeps listening, and the more energy is consumed.

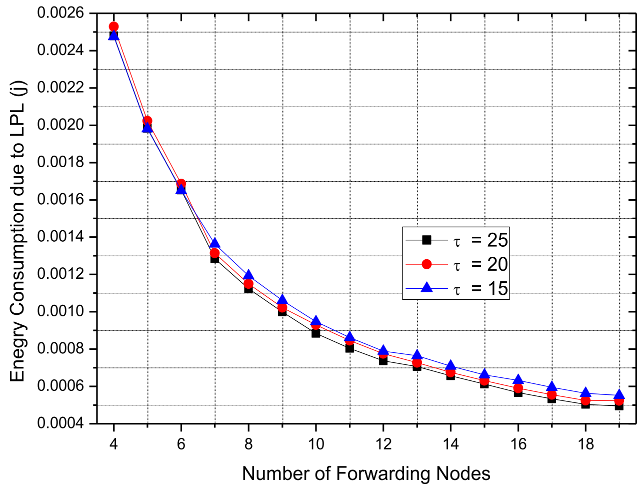

FIGURE 35. Energy consumption due to LPL when $\tau = 20$ (VIII).

When the number of nodes in the forwarding set of the node is the same ($N = 20$), and the duty length and the number of candidate nodes are different, the energy consumption of the node due to the listening is as shown in Fig. 36. When the number of candidate nodes of the node is the same, the greater the duty length of the node, the smaller the probability that the node wakes up in a slot, the longer the node remains listening and the more energy it consumes.

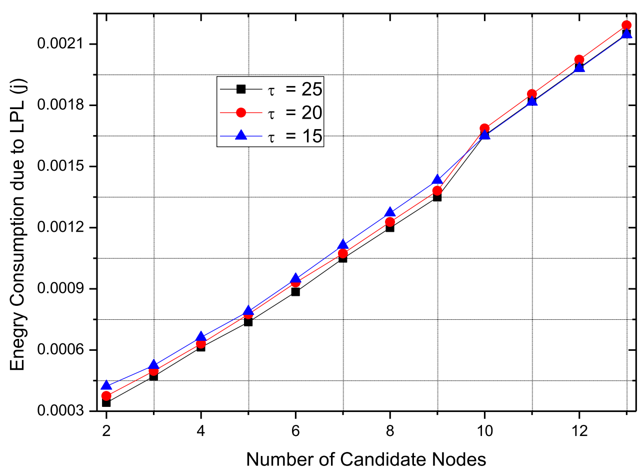

FIGURE 36. Energy consumption due to LPL when $\tau = 20$ (IX).

In the ASG scheme, the ACK packet sent by the node also has two forms. When the node is in the process of performing the first round of data transmission, the nodes in the forwarding set are randomly awake. At this time, the number of ACK packets sent by the node is the same as the number of ACK packets sent during the first round of data transmission in the ASUD scheme.

When the data transmission process proceeds to the second round, the nodes in the ASG scheme wake up evenly in the duty length in the form of grouping. Different from the ASUD scheme, in the ASG scheme, the node in the group listens to one slot and goes to sleep. In particular, if the current group is the last group, it will remain awake until the end of the data transfer. If the sender S wakes up in the at $slot_k$, the nodes in the $group_{\lceil ix/\tau \rceil}$ have already woken up. If $(\lceil kx/\tau \rceil - 1)(\tau/x) + 1 > k$, it means that the nodes in the $group_{\lceil ix/\tau \rceil}$ have not gone to sleep. Node S sends the packet directly to the nodes in the $group_{\lceil ix/\tau \rceil}$. In addition, the node S sends the ACK packet to the nodes of the remaining $x - \lceil kx/\tau \rceil$ groups, informing them that they do not need to listen to one slot, but directly enter the sleep state.If $(\lceil kx/\tau \rceil - 1)(\tau/x) + 1 \le k$, the nodes in the $group_{\lceil ix/\tau \rceil}$ have entered the sleep state. Node S waits for the nodes in the $group_{\lceil ix/\tau \rceil + 1}$ to wake up and will send an ACK packet to the nodes in remaining $x - \lceil kx/\tau \rceil - 1$ groups. In summary, in the subsequent transmission rounds, the number of ACK packets sent by the node is:

$$Q_i^{ACK-ASG-II} = Q_i^R \frac{P_i}{n_i p_i} + \sum_{k=0}^{\tau-1} a n_i P_k^{\text{one}} \tag{106}$$

If $(\lceil kx/\tau \rceil - 1)(\tau/x) + 1 > k$, $a = x - \lceil kx/\tau \rceil$; otherwise, $a = x - \lceil kx/\tau \rceil - 1$.

E. COMPARISON AND ANALYSIS OF THREE SCHEMES

In the previous chapters, we performed a detailed analysis of the performance of the MOR scheme, ASUD scheme, and ASG scheme. Since the duty cycle control is added to all three schemes, the following commonalities exist.

First, the greater the duty length of the node, the lower the probability that a node wakes up in a slot, and the greater the delay of the node. At the same time, the greater the duty length of the node, the longer the wake-up node keeps listening, and the more energy it consumes.

Secondly, the more the number of candidate nodes, the longer the waiting time for the n candidate nodes to wake up, the greater the delay. At the same time, the more the number of candidate nodes, the longer the node keeps listening and the greater the energy consumption.

Finally, the more nodes in the forwarding set, the shorter the time to wait for n candidate nodes to wake up, and the smaller the delay. At the same time, the more nodes in the forwarding set, the shorter the time that the node keeps listening, and the less energy it consumes.

Because the nodes wake up differently, the number of ACK packets sent by the nodes in the three schemes is different. We suppose that there is a network belonging to S_N defined in section V.A, and its density is 0.0034. The size of the Forwarding set of nodes in this network is shown in Fig. 37.The number of ACK packets sent by nodes in different schemes is shown in Fig. 38.

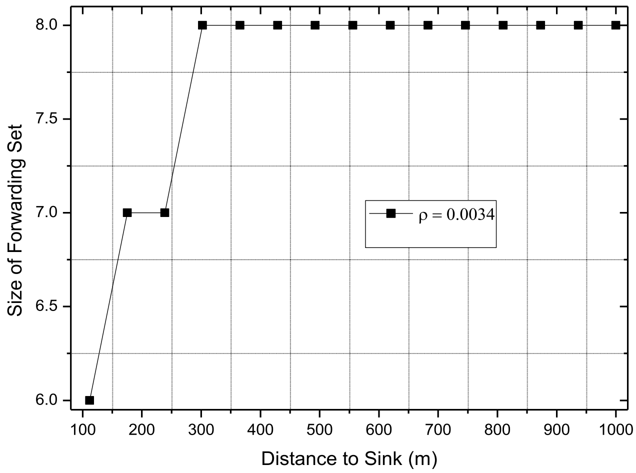

FIGURE 37. The size of the forwarding set when $\rho = 0.0034$.

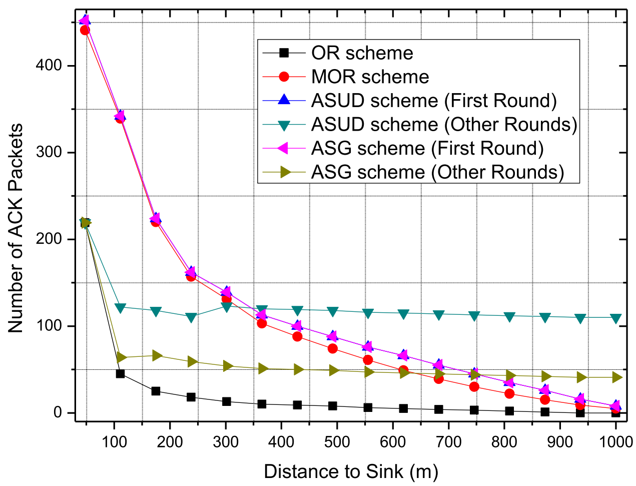

FIGURE 38. Actual number of ACK packets in different schemes.

The number of ACK packets sent by the node in the OR scheme is the smallest because it only needs to send ACK packets for the auxiliary packet transmission process. However, in the ASUD scheme and the ASG scheme, the node also needs to send ACK packets to coordinate the wake-up time and listening time of the node.

In the first round of data transmission, the number of ACK packets sent by the nodes in the three OR schemes that have been added to the duty cycle control is similar. This is because the nodes are randomly awakened during the first round of data transmission under these three schemes.

In the ASUD scheme and the ASG scheme, the ACK packets sent by the node during the first round of data transmission are different from other rounds. This difference is gradually reduced as the number of transmission rounds is accumulated. That is, when there are enough transmission rounds, we can think that the number of ACK packets sent by the node each time is as shown in Fig. 39.

Correspondingly, the energy consumed by the node due to sending of the ACK packets is shown in Fig. 40. As can be

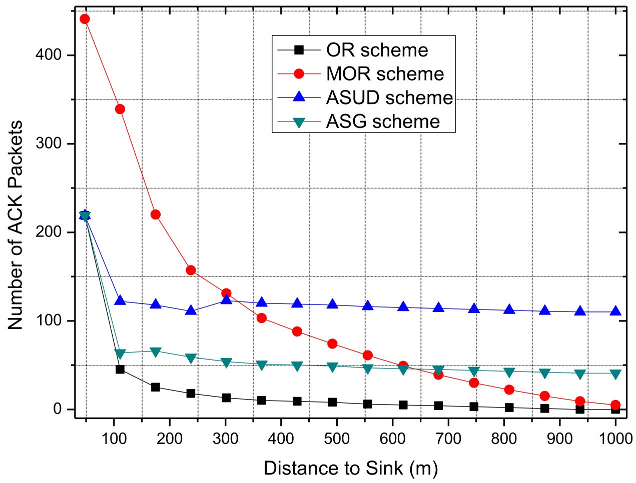

FIGURE 39. Theoretical number of ACK packets in different schemes.

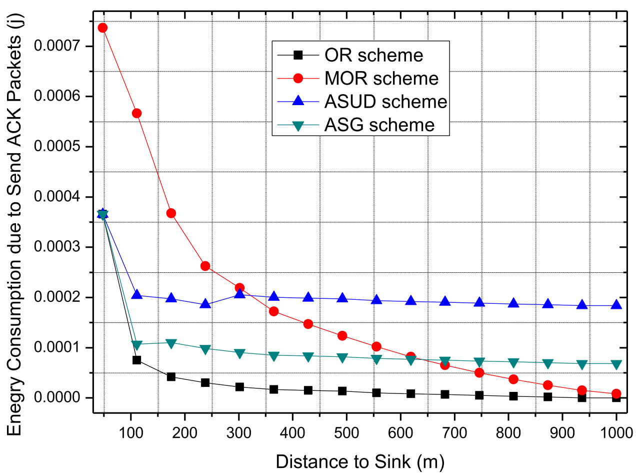

FIGURE 40. Energy consumed by sending ACK packets.

seen, the energy consumed by the node in the ASG scheme to send ACK packets is less than the ASUD scheme.

In the MOR scheme, the energy consumed by the ACK packet sent by the node is larger in the near-sink area than in other schemes, and is smaller in the far-sink area than other schemes. The energy consumed by the ACK packet sent by the node in the OR scheme is always smaller than other schemes.

We add up the energy consumed by the node to send the ACK packet and the energy consumed by the node to transmit other packets, and get the total energy consumed by the node to transmit the packets, as shown in Fig. 41.

Since the length of the ACK packet is very small relative to the length of the data packet, the energy consumed by the node to transmit the packets under 3 schemes is only slightly increased compared with the OR scheme.

Since then, we have compared the energy consumed by nodes in the three schemes due to the transmission of data packets, and found that the difference is not particularly large.

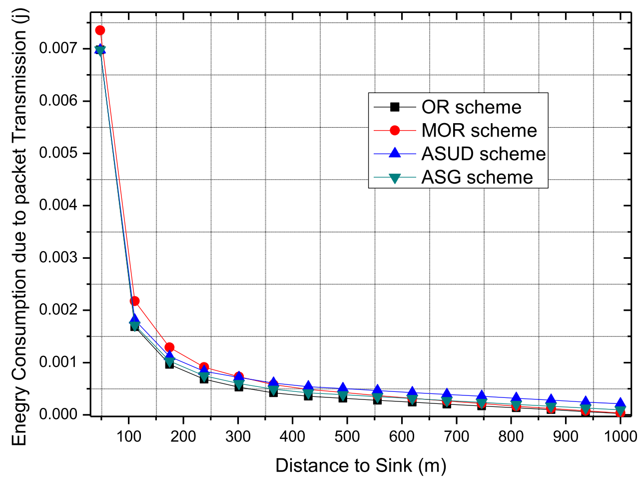

FIGURE 41. Energy consumed by sending packets.

Next, we continue to compare the delay of the node and the energy consumed by the node to keep listening.

When the size of the Forwarding set of a node is different, the one-hop delay of a node is as shown in Fig. 42.

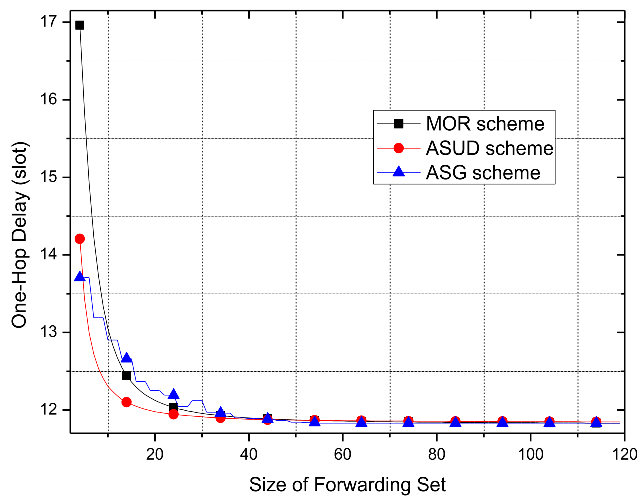

FIGURE 42. One-hop delay for different forwarding set sizes.

As the number of nodes in the forwarding set increases, the one-hop delay of the node tends to a constant. This constant is the average wake-up time of the sender:

$$\boxed{D = \sum_{k=0}^{\tau-2} \left(k * P_k^{\text{one}}\right) + (\tau - 1) * P_{\tau-1}^{\text{one}}} \tag{107}$$

It is not difficult to understand that as the number of nodes in the forwarding set increases, the N_n node wakes up faster and faster. As N approaches infinity, the time at which the N_n node wakes infinitely approaches zero, and the one-hop delay approaches infinitely close to the average wake-up time of the sender node.

From Fig. 42, we also found that when the number of nodes in the forwarding set is very large, the one-hop delay in the three schemes are very close. At this time, comparing the three schemes does not have much significance. In the network set S_N, we have three networks A, B and C. The density of the nodes in the network is $\rho_A = 0.0019$, $\rho_B = 0.0034$ and $\rho_C = 0.0065$. Below, we discuss the delays of nodes, the energy consumed by nodes due to the listening, and the energy consumed by nodes to transmit packets when using three schemes in networks A, B, and C, respectively.

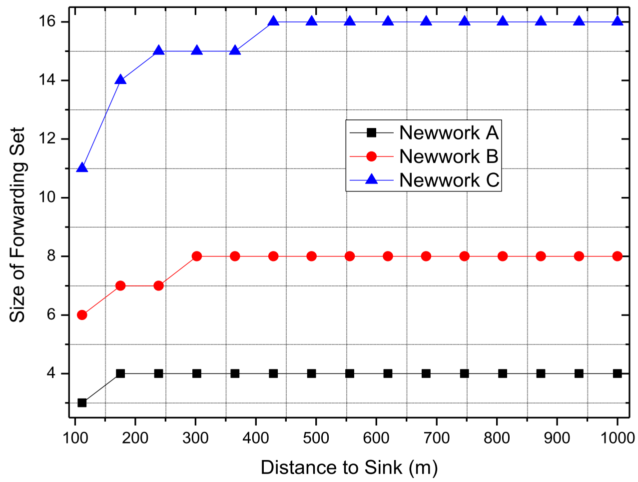

FIGURE 43. The size of the forwarding set in three networks.

Before that, we first give the size of the forwarding set of the nodes in the three networks, as shown in Fig. 43. In particular, the number of nodes in the forwarding set of the near-sink area node in network A is three, and the number of candidate nodes of the node in the network we define is three. In order to make the result more representative, we default that the number of nodes in the node forwarding is four.

According to the previous study, three different schemes are used in network A, and the delay of the nodes is shown in Fig. 44. The MOR scheme has the largest one-hop delay and the smallest in the ASG scheme.

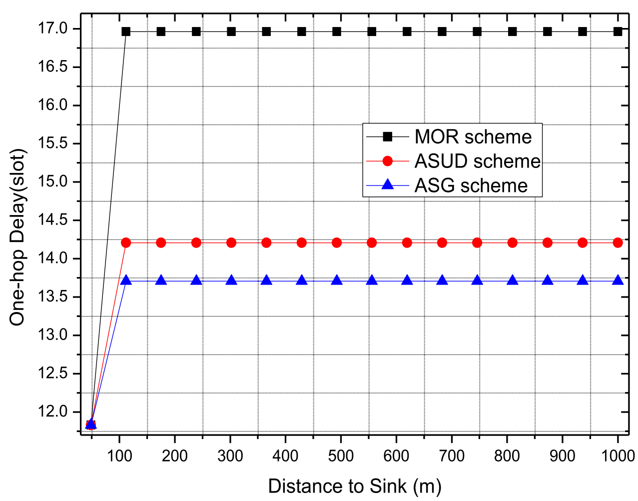

FIGURE 44. One-hop delay of nodes in three schemes (network A).

We add up the delay of each hop of the node, which is the end-to-end delay of the node, as shown in Fig. 45. The end-to-end delay of the nodes in the ASUD scheme and the ASG scheme is relatively close (smaller in the ASG scheme), and both are significantly smaller than the MOR scheme.

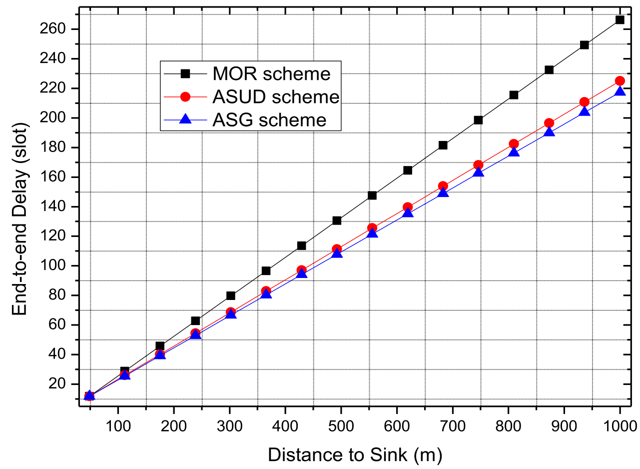

FIGURE 45. End-to-end delay of nodes in three schemes (network A).

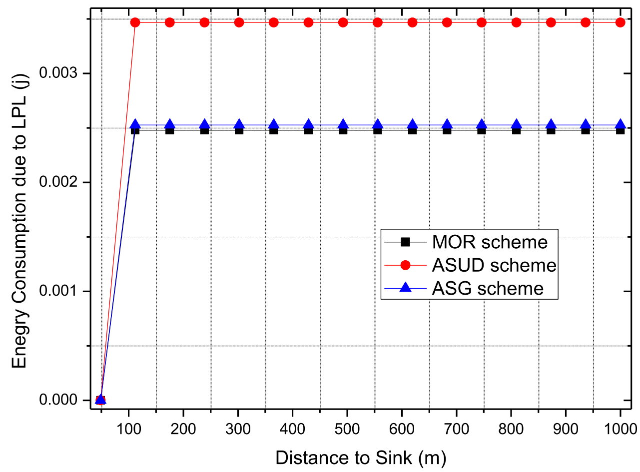

FIGURE 46. Energy Consumption due to LPL (network A).

The energy consumed by the node due to the listening is shown in Fig. 46. In particular, the node on the hop closest to the sink can transmit packets with the sink as soon as the node wakes up. Therefore, these nodes keep listening for 0 slots and the energy consumption is also 0 joules. The nodes in the ASUD scheme consume the most energy due to the listening, and the nodes in the MOR scheme consume the least.

The energy consumed by the node to transmit packets is shown in Fig. 47. In the near-sink area, it is obvious that the energy transmitted by the node in the MOR scheme is greater than the other two schemes.

We add the above two parts of energy to get the total energy consumed by the node in one round of data transmission, as shown in Fig. 48. Overall, the nodes in the ASUD scheme

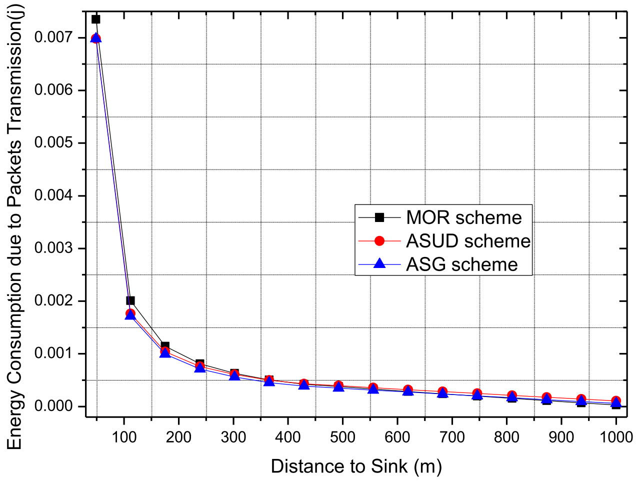

FIGURE 47. **Energy Consumption due to transmit packets (network A).**

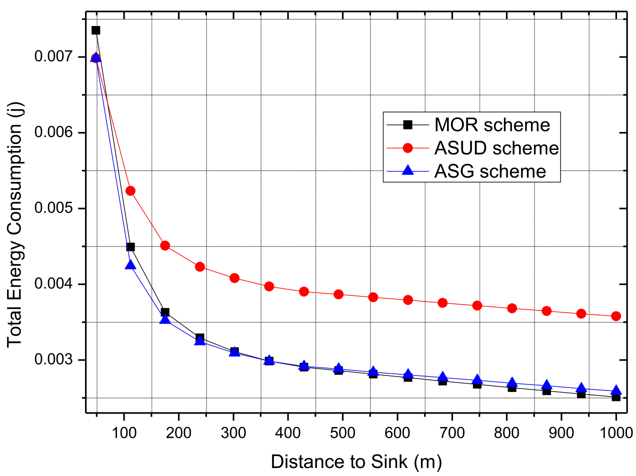

FIGURE 48. **Total energy consumption of nodes (network A).**

consume the most energy, and the total energy consumed by the nodes in the MOR scheme and the ASG scheme is similar.

When analyzing and comparing the three schemes, we found that the three schemes have different performances at different distances from the sink. To this end, we hope to find a unified standard to make a more reasonable evaluation of the three schemes.

First, when analyzing the delay of a node, we should pay more attention to the end-to-end delay of the node rather than one-hop delay. This is because the one-hop delay can only represent the situation of this hop, and cannot represent the actual situation of data packets transmitted throughout the network.

Second, we pay more attention to the delay of the nodes in the far-sink area. This is because the delay of the far-sink area represents the maximum end-to-end delay of the nodes in the entire network, which can represent the worst case and has practical guiding significance.

From these two perspectives, the competitiveness of the MOR scheme is obviously not as good as the other two schemes.

When analyzing the energy consumption of a node, we directly discuss the total energy consumed by the node (the energy consumed by the listening and the energy consumed by the transmitted packet), without distinguishing whether the energy is used for listening or for transmitting packets.

In addition, in the network model described in section III.A, we define the lifetime of the network as the time at which the first node in the network dies.

In the absence of outside interference, the first node to die must be the node that first depleted the energy. As can be seen from Fig. 48, the node on the hop closest to the sink consumes the most energy in a round of data transmission, that is, the node in this part must be the first dead node in the network. When the node in this part dies, even if other nodes still have a lot of energy left, it will not help.

Therefore, we should focus on the energy consumption of the node closest to the sink, the energy consumption of the other nodes is not important.

From this point of view, the MOR scheme is also inferior to the other two schemes.

After confirming that the MOR scheme is the third of the three schemes, we continue to discuss the ASUD scheme and the ASG scheme. Since the total energy consumed by the nodes in the ASUD scheme is the same as in the ASG scheme (the node on the hop closest to the sink). This means that the network using the ASUD scheme or the ASG scheme will die at the same time, so from the perspective of lifetime, the two schemes are essentially indistinguishable. From the point of view of the end-to-end delay of the node, the delay of the node in the ASG scheme is slightly lower than the ASUD scheme.

In summary, when the number of nodes in the forwarding set is very small, the ASG scheme is the best among the three schemes.

According to the above method, we can get the end-to-end delay of the node when using three different schemes in network B, as shown in Fig. 49. In network B, the end-to-end delay of the nodes in the MOR scheme and the ASG scheme is similar, and the ASUD scheme is slightly smaller than they are.

The total energy consumed by the nodes in Network B is shown in Fig. 50. Overall, the nodes in the MOR scheme consume the most energy and the ASG scheme consumes the least.

Since the end-to-end delay of the node in the MOR scheme is the largest, and the node consumes the most energy, it is first excluded. In the remaining two schemes, the end-to-end delay of the nodes in the ASUD scheme is smaller with the same energy consumption. Therefore, we think that when the number of nodes in the forwarding set is moderate, the ASUD scheme is the best of the three schemes.

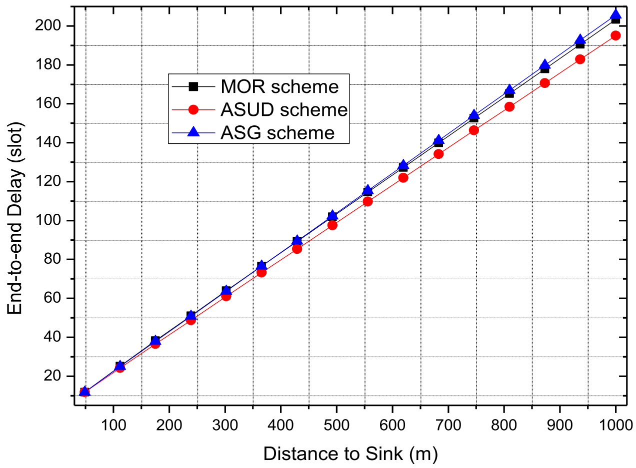

FIGURE 49. End-to-end delay of nodes in three schemes (network B).

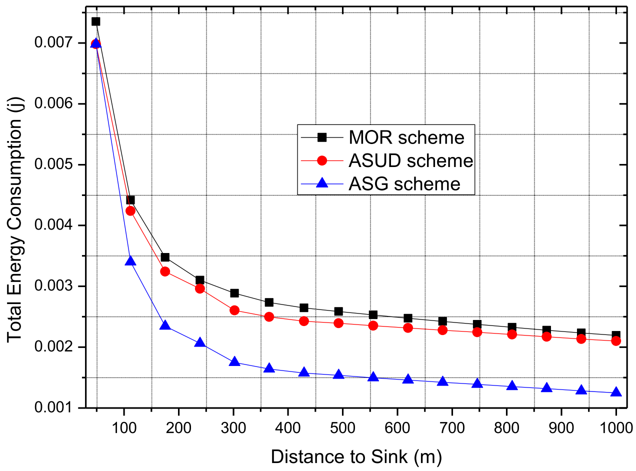

FIGURE 50. Total energy consumption of nodes (network B).

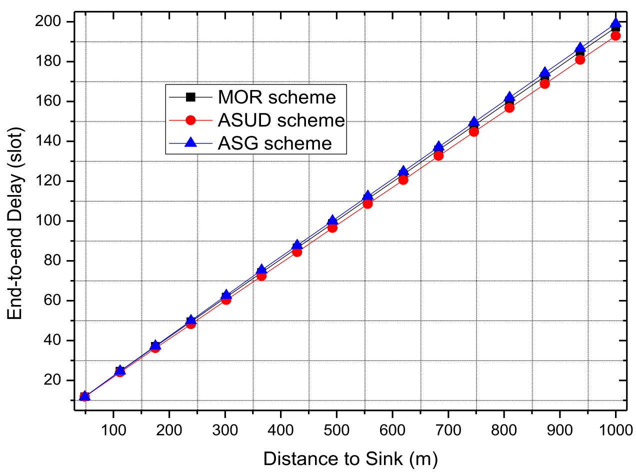

FIGURE 51. End-to-end delay of nodes in three schemes (network C).

Similarly, we can get the end-to-end delay and total energy consumption of the nodes in network C, as shown in Fig.51 and Fig. 52.

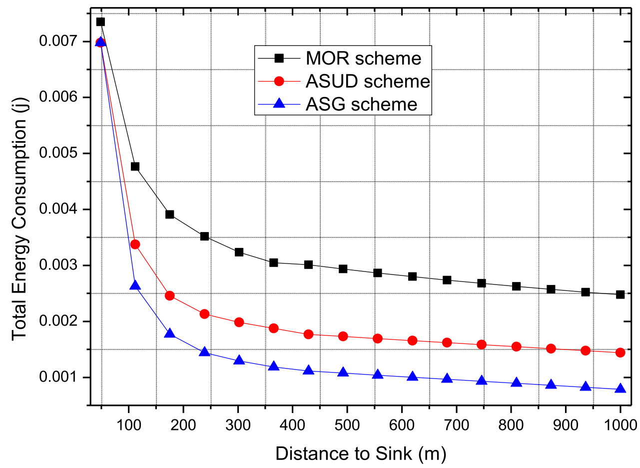

FIGURE 52. Total energy consumption of nodes (network C).

When comparing the three schemes in network C, we first consider the MOR scheme and the ASUD scheme separately. It can be seen from Fig. 51 and Fig. 52 that the end-to-end delay of the nodes in the MOR scheme is larger than the ASUD scheme, and the total energy consumed by the nodes in the MOR scheme is larger than the ASUD scheme. Therefore, the ASUD scheme is superior to the MOR scheme.

For the ASUD scheme and the ASG scheme, the energy consumption of the two can be considered to be the same (the lifetime is the same), and the end-to-end delay of the ASUD scheme is slightly smaller than the ASG scheme. Therefore, we think that when the number of nodes in the forwarding set is relatively large, the ASUD scheme is the best choice among the three schemes.

When comparing the three schemes in network C, we first consider the MOR scheme and the ASUD scheme separately. It can be seen from Fig. 51 and Fig. 52 that the end-to-end delay of the nodes in the MOR scheme is larger than the ASUD scheme, and the total energy consumed by the nodes in the MOR scheme is larger than the ASUD scheme. Therefore, the ASUD scheme is superior to the MOR scheme. For the ASUD scheme and the ASG scheme, the energy consumption of the two can be considered to be the same (the lifetime is the same), and the end-to-end delay of the ASUD scheme is slightly smaller than the ASG scheme. Therefore, we think that when the number of nodes in the forwarding set is relatively large, the ASUD scheme is the best choice among the three schemes.

From the above analysis, we can draw the following conclusions.

First, the MOR scheme is the least competitive among the three schemes. The nodes in the MOR scheme are randomly awake. Especially the node closest to the sink needs to send more ACK packets, which makes the lifetime of the whole network shorter. In addition, while shortening the lifetime, the MOR scheme does not reduce the end-to-end delay of the nodes in the network. Overall, none of them can compete with the other two schemes.

Secondly, both the ASUD scheme and the ASG scheme reduce the ACK packets sent by the node to some extent.

Especially the node closest to the sink, compared to the OR scheme, the ACK packet sent has not increased at all, and it has no effect on the lifetime of the entire network. In the case of the same lifetime in the two schemes, we only need to choose according to the end-to-end delay of the node. In these two schemes, the end-to-end delay of the nodes is not particularly different. Therefore, when we do not know the number of nodes in the specific forwarding set, the two schemes are a good choice.

VI. PERFORMANCE COMPARISON AND ANALYSIS

In this paper, in order to improve the receiving rate and minimize the energy consumption of the node, we add the duty cycle control to the Opportunity Routing (OR) scheme and propose the Modified Opportunistic Routing (MOR) scheme. The sensor nodes in the MOR scheme wake up periodically, and the nodes stay asleep for most of the time, thus reducing the node's energy consumption. But at the same time, during the data transmission, since the sensor node may still be in a sleep state, the transmission process must be interrupted until the number of waking candidate nodes reaches the threshold n. Obviously, this increases the one-hop delay and the end-to-end delay of the nodes. In order to reduce the delay of the node, we propose two new schemes, namely the Active Slot Uniform Distribution (ASUD) scheme and the Active Slot Group (ASG) scheme. In both schemes, the sender node waits for n candidate nodes to wake up for a shorter time and has a smaller delay (compared to the MOR scheme).

Below, we will continue to explore the difference in performance, regarding the three schemes proposed in this paper that increase the duty cycle control, and the OR scheme.

A. PERFORMANCE ANALYSIS OF ENERGY CONSUMPTION

The energy consumed by nodes in WSNs consists of two parts, one part is because the node transmits the data packet, and the other part is because the node keeps listening.

In section V.E, we have given the way to calculate the total energy consumed by nodes in the MOR scheme, ASUD scheme, and ASG scheme.

For the OR scheme, we give a method for calculating the energy consumed by a node due to the transmission of packets in section V.A. When calculating the energy consumed by the sensor node due to the listening, the nodes in the OR scheme are always in the listening state, and the corresponding energy consumption is:

$$E_{OR}^{LPL} = P_{LPL}T \tag{108}$$

Where P_{LPL} represents the power (in W) at which the node remains listening, and T represents the length of the entire duty length (in s).

Taking the networks A, B, and C defined in section V.E as an example, the total energy consumed by the nodes is shown in Fig. 53, Fig. 54, and Fig. 55, respectively.

When analyzing the energy consumption of a node, we focus on those nodes that consume the most energy, because the lifetime of these nodes determines the lifetime

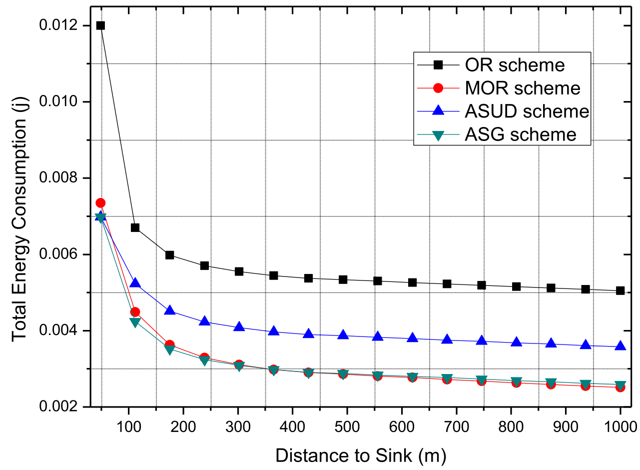

FIGURE 53. Total energy consumption of nodes (network A).

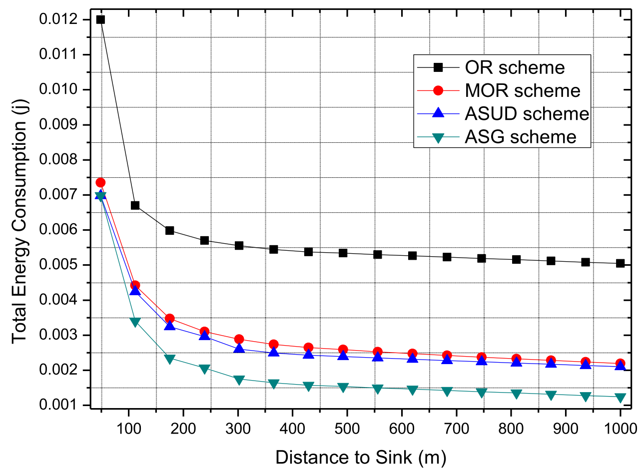

FIGURE 54. Total energy consumption of nodes (network B).

of the entire network. From this perspective, regardless of the node density in the network, the lifetime of the network using different schemes is the same. We consider the energy consumption of the node closest to the sink as the representative of the energy consumption of the nodes in the entire network. Then, when the density of the nodes is different, the energy consumed by the nodes in the network using the same scheme is the same.

In summary, we can see that the energy consumption of nodes in the MOR scheme, ASUD scheme and ASG scheme is reduced by 38.75%, 41.83% and 41.83%, respectively, relative to the OR scheme. We suppose that the initial energy of the nodes in the network are the same, then the lifetime of the network using the MOR scheme, ASUD scheme and ASG scheme is extended by 63.27%, 71.92% and 71.92%, respectively, compared to the network using the OR scheme.

B. PERFORMANCE ANALYSIS OF DELAY

In this paper, in order to reduce the energy consumption of the node, we added the duty cycle control in the OR scheme. In the MOR scheme, we do not control the time the node

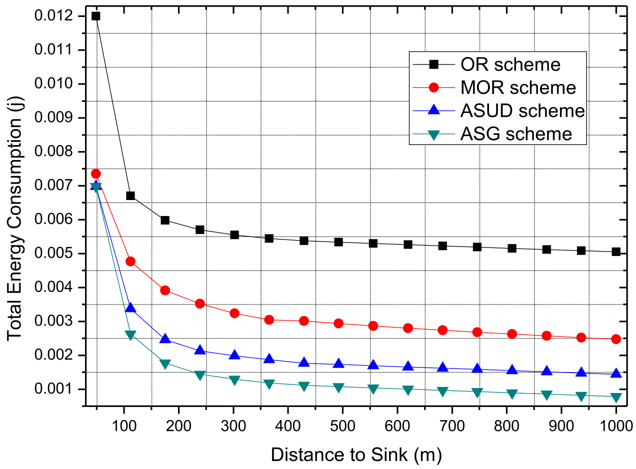

FIGURE 55. **Total energy consumption of nodes (network C).**

wakes up. Each node wakes up randomly in a certain slot. This randomness brings a lot of delay to the node. In order to be able to reduce the delay of the node, we try to change the wake-up time of the node. Therefore, we have proposed two schemes, ASUD scheme and ASG scheme. In these two schemes, the wake-up time of the node is not random, but is adjusted by the actual situation of the network. In the ASUD scheme, the nodes in the forwarding set wake up evenly in the duty length. In the ASG scheme, the nodes in the forwarding set are grouped first (n nodes per group), and wake up evenly in the duty length according to the group. From the comparison in section V.E, we know that the delay of the nodes in the ASUD scheme and the ASG scheme is reduced compared to the MOR scheme.

However, the delay of the nodes in the ASUD scheme and the ASG scheme is still greater than the delay of the nodes in the OR scheme. We added duty cycle control in ASUD scheme and ASG scheme, which reduced the node's energy consumption and increased the node's delay. Due to the addition of duty cycle control, some nodes are in a sleep state at a certain time, and the originally coherent packet transmission process is interrupted, which leads to delay. In all the routes that use the duty cycle control, the delay of the node will increase, which is a defect of the duty cycle control itself.

VII. CONCLUSION

In this paper, we first propose a Modified Opportunistic Routing (MOR) scheme to make duty cycle control applicable to duty cycle based WSNs. Then, to reduce the delay of data routing, we propose Active Slot Uniform Distribution (ASUD) scheme and the Active Slot Group (ASG) scheme. In ASUD scheme, the nodes wake up evenly in the duty length, that is, each node wakes up at the same time interval. In ASG scheme, first every n nodes are grouped, and all groups are uniformly awakened in the duty length. We have carried out detailed analysis and calculation of the proposed algorithm. We found that if the OR scheme is simply applied to the duty cycle based WSNs, its energy consumption is better than that in the non-duty cycle based WSNs. The ASUD and ASG scheme are superior to MOR scheme in terms of the energy consumption of the slave node (the energy consumption of the node closest to the sink) or the end-to-end delay of the node.

In future research and analysis, we can improve in the existing scheme. For example, adjust the duty cycle of some nodes appropriately, so that the one-hop delay and the end-to-end delay are reduced when the network lifetime is unchanged.

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