Received April 12, 2019, accepted April 25, 2019, date of publication April 30, 2019, date of current version May 9, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2913885

To Reduce Delay, Energy Consumption and Collision through Optimization Duty-Cycle and Size of Forwarding Node Set in WSNs

FEIHU WANG[1], WEI LIU[2], TIAN WANG[3], MING ZHAO[1], MANDE XIE[4], HOUBING SONG[5], (Senior Member, IEEE), XIONG LI[6], AND ANFENG LIU[1]

[1]School of Computer Science and Engineering, Central South University, Changsha 410083, China
[2]School of Informatics, Hunan University of Chinese Medicine, Changsha 410208, China
[3]College of Computer Science and Technology, Huaqiao University, Xiamen 361021, China
[4]School of Computer Science and Information Engineering, Zhejiang Gongshang University, Hangzhou 310018, China
[5]Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA
[6]School of Computer Science and Engineering, Hunan University of Science and Technology, Xiangtan 411201, China

Corresponding author: Mande Xie (xiemd@zjgsu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61772554, Grant 61572526, and Grant 61572528, and in part by The Natural Science Foundation of Zhejiang Province under Grant LY17F020032.

ABSTRACT Fast and energy efficient transmission is an important and challenging issue for wireless sensor networks (WSNs). Energy efficiency is also an important concern of green communication in WSNs. Optimizing the duty cycle (DC) of nodes and the size of forwarding node-set (SFNS) can effectively reduce the delay and improve energy efficiency. In this paper, we conclude that an optimal DC value can minimize the delay when the number of SFNS is constant. The reason why the delay is larger when the DC is smaller than the optimal value is that when the sender sends data, it needs to wait for the forwarding node to wake up which causes a large delay. When DC is larger than the optimal value, the delay is also larger because SFNS has more than one node in the awake state, which causes conflicts and increases the delay. For energy consumption, the sender with smaller DC has fewer collisions, so the energy consumption is less. Similarly, when DC is constant, SFNS also has an optimal value, which minimizes the delay. Based on the theoretical analysis, an Optimization Duty-Cycle and Size of Forwarding Node Set (ODC-SFNS) scheme is proposed to reduce delay and improve energy efficiency. The main optimization methods adopted are as follows: (a) For dense and high-DC networks, one hop delay and the number of hops needed for the packet to reach sink can be reduced by appropriately limiting the SFNS, thus the end-to-end delay can be effectively reduced. (b) For sparse and low-DC networks, increasing the DC in the far sink region can reduce delay while not reducing the network life, and improve energy efficiency. Compared with the traditional scheme, the ODC-SFNS scheme can reduce the end-to-end delay by 20.52%-79.96%, and it has dramatically increased energy efficiency. Moreover, its scope of application is broader than previous strategies.

INDEX TERMS Wireless sensor networks, delay, green communication, duty cycle, forwarding set.

I. INTRODUCTION

Nowadays, wireless mobile communication technology and Internet of Things [1]–[7] have reached a new level. Wireless mobile communication technology is about to enter the 5G era, and the Internet of Things technology is becoming more mature. With their progress, WSNs have also been used more and more widely [8]–[11]. However, sensor nodes are mostly battery-powered [12]–[16], it is often impossible or costly to replace batteries, especially those deployed in battlefield environments or in harsh natural environments. Therefore, it is important to improve energy efficiency [10], [12], [16], [25], [26]. At the same time, improving energy efficiency is also a main concept of "green communication" which is widely advocated at present. On the other hand, due to limitation of a single sensor in terms of communication distance, data are often transmitted to sink nodes by multi-hop mode, but this will bring

The associate editor coordinating the review of this manuscript and approving it for publication was Wei Wei.

about undesirable transmission delay [11], [17], [18], [10], [12], [16] and reduce the real-time performance of events. So how to reduce the transmission delay is also an important issue in many WSNs research [11], [13], [15], [17], [18].

In fact, there have been a lot of researches on improving the energy efficiency and reducing the delay for the wireless sensor network [2], [10], [12], [17], [18]. The application of the duty cycle mode of the sensor node is an effective way to improve the energy efficiency [2], [17], [18], [27]. In the duty cycle mode, the nodes periodically awake/sleep. When the node is in the sleep state, the wireless receiving device is turned off, which can greatly save energy. Since the energy consumption of awake state is more than two orders of magnitude higher than that of sleep state, in order to save energy, nodes should be kept in sleep state as far as possible [2], [17], [18], [27]. However, when the node is in the sleep state, it cannot sense data or communicate with each other. Therefore, the smaller the duty cycle (the ratio of the time when the node is in the awake state to the length of the entire cycle) of the node, the higher the probability that the receiver will be in sleep state when sender has data to send. When all receivers are in the sleep state, sender must wait for their receivers to wake up to send data, which leads to the increase of the delay of data routing [2], [17], [18], [27].

In addition, the delay of data routing is also related to the number of receivers, that is the Size of Forwarding Node Set (SFNS) [28], [29]. Previous studies found that in the low duty cycle network, when the sender's SFNS is large, the delay will be small. Because when the sender needs to send data, data routing can be performed as long as one node in the Forwarding Node Set (FNS) is awake. Therefore, the greater the SFNS, the greater the probability that the forwarding node wakes up when the sender has data to send, and thus the smaller the delay [28], [29].

Besides, the delay of data routing is related to the selection of forwarding nodes by sender [28], [29]. The wireless communication range can be abstracted as a circle with sender as its center and broadcast radius as its radius. And the distances of different nodes in sender's FNS to sink are different. Obviously, if sender selects a node closer to sink as relay node, it will make one hop forward distance towards sink larger, which will make the hop number of packets from sender to sink smaller. Extra hop will bring extra delay, so the smaller the number of hops for data route, the smaller the end to end delay. However, in asynchronous wireless sensor networks, it is not easy for sender to select forwarding node closest to sink for data routing [28], [29]. This is because the forwarding node closest to sink is not necessarily awake when sender has data to send because nodes work asynchronously. As a result, the sender has two choices. The first is that the sender waits for the forwarding node closest to sink to wake up, which increases the delay of waiting. The second is that the sender selects the node closest to sink in the waking forwarding node to route. In this situation, although the sender need not to wait, the number of hops will increase because the forwarding node selected is always not the closest to the sink, which increases the delay [28], [29].

Based the above situation, Naveen and Kumar [28] propose a multi-objective optimization strategy to optimize energy consumption and delay. However, this method assumes that the duty cycle in WSNs is low. In WSNs with low duty cycle, because of the short wake time of nodes, the probability of multiple forwarding nodes waking up at the same time is relatively small, so that the probability of channel collisions is low. On the other hand, due to the low duty cycle of nodes, the probability that the sender has multiple receivers at the same time when sending data is relatively low. Thus, only the energy consumption of one sender and one receiver node need to be calculated when calculating energy consumption. In the low duty cycle networks, they get this conclusion: the larger the duty cycle of the node, the smaller the delay, the larger the SFNS of sender is, the smaller the delay is.

However, in many applications of wireless sensor networks, low duty cycle wireless sensor networks are just one type of them. There are numerous different types of networks in current applications. For example, some applications require a very dense deployed network. Thousands of sensor nodes are deployed in a small area. While in some applications, the duty cycle of the sensor nodes is required to be large. In other applications, not only are the nodes deployed dense, but the node's duty cycle is also large [30]–[33]. In these networks, the above conclusion may be untenable. The reason is that with the increase of SFNS or duty cycle, collision becomes the main factor of routing delay and node energy consumption. When sender has packet to send, if multiple forwarding nodes are in the awake state, they will receive the sender's packet at the same time so that the acknowledgment message from multiple forwarding nodes will collide at the sender, which makes the sender cannot successfully receive the acknowledgment message, which may result in unsuccessful transmission. [34]. The sender will continue to send packet in the next time slot until the transmission is successful, which will increase the delay of the data routing. Moreover, the energy consumption will also increase due to multiple nodes receive and send packet when conflict occurs.

It can be seen that the previous research suitable for low duty cycle cannot be applied to all networks universally, and there is no strong theoretical guidance in designing network applications, resulting in low network performance and rising costs.

This is a simplification of the network that ignore the delay and additional energy consumption caused by the collision between multiple forwarding nodes. It is only an ideal situation, which makes it difficult to be applied to the actual network. At present, there is no research that can be applied to delay and energy consumption of sensor networks in various cases. In particular, there is a lack of theoretical research results to simultaneously optimize delay and energy consumption by optimizing the network's duty cycle and the size of forwarding node set (SFNS).After in-depth study, an optimal relationship among the duty cycle, SFNS, data routing and energy consumption considering the communication collision between nodes is proposed in this paper, which can effectively guide the design and optimization of data routing. Based on the theoretical analysis results of this paper, an Optimization Duty-Cycle and Size of Forwarding Node Set (ODC-SFNS) scheme is proposed to reduce delay and improve energy efficiency for WSNs. In summary, the main research contributions of this paper are as follows:

(1) This paper first theoretically analyzes the delay and energy consumption calculation method of data routing in the case where the network's duty cycle and SFNS are known. Previous studies have only focused on low duty cycle networks, and did not consider communication collision. The model of this paper considers the collision, which extends the model to any network, and optimizes the delay and energy consumption brought by communication collision. The research in this paper greatly enriches the previous research and is more applicable to the actual network, which has a desirable theoretical guiding significance.

(2) The theoretical analysis results of this paper reveal the complex relationship among duty cycle, SFNS, delay and energy consumption in WSNs. An important conclusion obtained in this paper is: When the duty cycle $\left(1/\tau\right)$ of a node multiplied by the number (n) of FNS is equal to 1, that is, when $n \times \left(1/\tau\right) = 1$, the delay is optimized. At this time, the cycle length of a node is τ slots and one slot is selected as the work slot (or active slot), which means the duty cycle of the node is $1/\tau$.

According to the research conclusions of this paper, the previous research can be well explained. For example: for the low duty cycle network, previous studies have considered that it is possible to effectively reduce the delay by increasing the duty cycle of the node or increasing the SFNS. That's because, in the network of low duty cycle, $1/\tau$ is very small, then $n \times \left(1/\tau\right) < 1$. Thus, either increasing the duty cycle or increasing SFNS can make the value of $n \times \left(1/\tau\right)$ closer to 1, which reduces the delay of the network. For a network with a high node density and high duty cycle, $n \times \left(1/\tau\right) > 1$. At this time, there are multiple nodes waking up in the same time slot, which results in a communication collision and brings higher energy consumption and delay. Therefore, reducing the node's duty cycle or reducing the node's deployment density can improve network performance (which means the delay will be reduced and the lifetime will be improved).

(3) According to our theoretical analysis results, an Optimization Duty-Cycle and Size of Forwarding Node Set (ODC-SFNS) scheme is proposed to reduce delay and improve energy efficiency for WSNs. The ODC-SFNS scheme mainly optimizes the delay and energy efficiency by adjusting two important parameters: duty cycle and SFNS. The method is: for a given network, when $n \times \left(1/\tau\right) > 1$, which means the network duty cycle or SFNS is relatively large, so that the probability of conflict is relatively high when nodes communicate. At this time, the duty cycle of the node can be reduced to optimize the number of communication collisions in the network to reduce delay of the network while improving the network lifetime. However, the node maybe not adjust the duty cycle due to the limitation of the monitoring, when that happens, reducing SFNS by limiting forwarding node set of nodes also can reduce delay and energy consumption. Regardless of whether $n \times \left(1/\tau\right) > 1$ or $n \times \left(1/\tau\right) < 1$, ODC-SFNS can optimize network performance by adaptively adjusting duty cycle and SFNS. The method is: For the network with $n\times \left(1/\tau\right) < 1$, there is more residual energy in the region far from the sink. The value of $n\times \left(1/\tau\right)$ can be brought closer to 1 by increasing the duty cycle of nodes with residual energy, thus reducing the delay. For the network with $n \times \left(1/\tau\right) > 1$, we reduce SFNS by limiting the area of FNS, in this way, the value of $n\times \left(1/\tau\right)$ will also be brought closer to 1. Furthermore, the duty cycle of the region far from the sink can also be increased and the area of the region of sender's forwarding nodes can be further reduced thereby reducing the SFNS.

Reducing the size of forwarding nodes area can also make the distance of one hop forward longer, thus reducing the number of hops in the whole routing process. By this way, the delay of the network will be effectively further reduced.

(4) The validity of the strategy proposed in this paper is confirmed by the in-depth theoretical analysis results. Compared with the traditional scheme, the ODC-SFNS scheme can reduce the end-to-end delay of the network by 20.52%-79.96% and make the energy efficiency reach above 90%. The scope of application is wider than previous strategies.

The rest of this paper is organized as follows: In Section 2, the related work is introduced. The network model and problem statement are presented in Section 3. Then, the theoretical results of the optimization among duty cycle, SFNS, delay and energy consumption are presented in Section 4. The ODC-SFNS scheme is presented in Section 5. Performance analysis of the scheme is presented in Section 6. Finally, Section 7 provides conclusions.

II. RELATED WORK

With the development of microprocessor technology, sensor based deivces has developed rapidly, which has contributed to the boom in the Internet of Things (IoT) booming. According to research, the number of communication devices connected to IoT has exceeded the number of people, reaching an astonishing 9 billion [25]–[39]. With the huge increase in the number of sensing devices connected to IoT [1]–[3], [40], [41], the human ability to obtain real-time and large scale data has been greatly promoted [42], [43]. These sensor based devices connected to the Internet have powerful computing capabilities that can be combined with artificial intelligence technologies such as intelligent recognition [44], [45], image processing [46], [47], and information security technology [48]–[52]. Network centers also evolve from the central network to the edge of the network, from cloud computing [38], [48]–[50] to edge computing [53] or fog computing [41], [42], [50] reflecting the current development of network computing model trend.

Sensor based network is the most important network of IoT [2], [11], [13], [16], [17], [18]. In such sensor based network, sensor nodes consist of sensor, battery, data processing and communication component. A large number of sensor nodes are deployed in scenarios that need to be monitored. The sensor nodes self-organizing to form a network, and work together to complete the data sensing and data collection tasks, such as weather monitoring, traffic monitoring, earthquake detection, noise level testing, health monitoring and other monitoring [54], [55]. Usually, the sensor node routes the sensed data to the sink (or control center) through multi-hop routing. The sink analyzes and processes the data, and takes corresponding control measures, thereby achieving automatic control. In many applications, sensed data is required to be quickly routed to the control center, as delayed data routing can cause significant losses. For example, in the monitoring of industrial production lines, fire monitoring requires that the delay of data routing is as small as possible [11], [17], [18]. On the other hand, due to economic considerations, in order to minimize manufacturing costs, sensor nodes tend to be manufactured in a relatively small volume, powered by batteries, and sometimes cannot be replaced due to the harsh environment conditions. And in some environment, the cost of replacement is too high. Due to the limited energy, how to use energy effectively is one of the important research contents [12]–[16].

In summary, energy efficiency and low delay are important research contents in WSNs. The following is a summary of some research closely related to this paper.

The research on delay in duty cycle based wireless sensor network [2], [17], [18], [27], [28]. The working mode with duty cycle can effectively save energy. Thus, duty cycle based on WSNs have been widely used and researched [28]. In the duty cycle based on WSNs, it is obviously the smaller the duty cycle of the node, the more energy can be saved. However, as the duty cycle becomes smaller, the delay will be larger. There are many researches about delay reduction and energy efficiency.

The data collection strategy of the Time Division Multiple Access (TDMA) mechanism is a scheduling strategy that the time slots are strictly arranged [2]. In the TDMA data collection method, the time period is divided into several time slots. The node switches to the awake state during data operation, and the node switches to sleep state when there is no data operation to save energy and avoid conflicts. The data collection for such networks translates into how to assign a minimum number of slots to each node so that the nodes can send all the data in the network to the sink after performing data operations in these allocated slots. In such data collection method, the last slot of all nodes for data operation is the delay of the whole network. Research has proved that it is a NPC problem to assign the smallest slot to each node and make the delay smallest in the TDMA scheduling algorithm. Therefore, many approximate optimized TDMA scheduling algorithms have been proposed. [2]. In such a network, the node will awake when only data operations are required, while it stays in sleep state in other slots, so its energy consumption is the most economical. Moreover, the delay of this type of research is very close to the theoretical optimization value. Although the performance of the TDMA scheduling algorithm is good, the data collection method of the TDMA is only suitable for some networks. Because the TDMA algorithm adopts a central algorithm. The control center has to acquire the topology of the entire network and know whether each node generates a data packet. And after the calculation, the data operation time slot of each node is set by the control center.Therefore, it is not suitable for the network with dynamic data generation. All the nodes in the network need to follow the given slot operation after the scheduling algorithm is generated. If the network topology changes, the scheduling algorithm needs to be recalculated.

The above TDMA strategy is suitable for data fusion and non-fusion networks. For data fusion networks, a data collection strategy called convergecast is also proposed [2], [56]. Convergecast is for a special type of data fusion network. In such a network, any number of data packets can be merged into one data packet after encountering. This type of network is often used to the application that finds the average observed value, the maximum observed value, or the minimum observed value of the monitored object. For example: in the monitoring of crops, the maximum value, minimum value, and average value, etc. of the temperature and humidity of the observed object need to be calculated. Therefore, any number of data packets can be merged into one data packet after encountering, thereby greatly reducing the data amount and saving energy. Convergecast's design has two goals: reduce delay and energy consumption. The main research of Convergecast strategy can be divided into two types: one is tree-based data collection strategy [56], and the other is data collection strategy based on cluster network structure [2]. The tree-based data collection strategy is to transform the network into a tree with a root node, and data is collected from the leaf nodes to the sink layer by layer [56]. In the convergecast strategy, a two-stage data collection strategy is generally adopted to reduce the energy consumption of data collection. The first stage is the data receiving stage. The node only receives data at this stage without sending any packet. The second stage is the data transmission stage. The node fuses all the collected data packets into one data packet and sends them at a time. Once the data is sent, the node no longer accepts the data, which means no data operation is performed. This ensures that each node can fuse the received data packets into a data packet, which makes it possible to send only one data packet, thereby reducing energy consumption [2], [56]. The cluster based convergecast data collection strategy divides the network into clusters. Then, cluster member nodes send data to the cluster head. The cluster head fuses the collected data packets into one data packet. Then, all cluster heads perform the data collection similar to the tree-based strategy. The data collection of cluster based convergecast can be performed in parallel in the cluster, so the delay of data collection is relatively small. Li et. al. [2] proposed a convergecast strategy for unequal divided clustering networks. In the proposed strategy, the radius of the cluster far from the sink is smaller, and the radius of the cluster near the sink is bigger. In this way, the cluster far from the sink first completes the data collection inside the cluster, and starts the data transmission between the clusters. And at this time the cluster near the sink just completes the data collection inside the cluster, thus enabling the entire network to perform parallel data collection, so the delay is small. And the cluster head node only needs to perform state transition once to during the data collection, so the energy consumption is small.

The above data collection strategy is all with strict time slots. Therefore, the time slots of each node in the network are strictly arranged before data collection. The advantage of this method is that the nodes only wake up when performing data operations and stay sleep when there is no data to operate, thereby reducing the consumption of energy and time. However, many networks don't necessarily generate data periodically. Most monitoring networks generate according to the occurrence of the event, so the above TDMA scheduling strategy is not applicable to such a network.

There are two types of data networks that generate data from time to time. One is synchronous networks (in fact, TDMA scheduling is also aimed at synchronous networks) [2], [56]. In such networks, the time of nodes is synchronized [2], [56]. Another kind of network is asynchronous network where the clock of each node is not synchronized. The sleep/awake conversion of each node is determined independently according to its own time cycle. For data routing, the delay of the synchronous network is smaller than the delay of the asynchronous network [2], [56]. That's because in the synchronous network, the active slots of the adjacent two nodes of multi-hop data routing can be made continuous by adjusting the active slots of the nodes appropriately. In this way, pipeline routing manner can be formed, so that there is no pause in the packet routing process. In asynchronous networks, since the active slots of nodes are independently determined [17], [18], [32], the active slots of adjacent two nodes in multi-hop routing are not necessarily continuous and may be separated by multiple slots. As a result, sender needs to wait for multiple slots to transmit data, which increases the delay [17], [18], [32].

Although the delay in the synchronous network is small, it takes more system costs. Due to slot offset or other reasons, the synchronous networks often need to maintain synchronization through information exchange among nodes, and this operation is performed periodically throughout the network.Therefore,maintaining network synchronization requires a certain cost [2], [56]. Asynchronous networks do not need to maintain system synchronization, so the system cost is small. Due to the flexible and convenient deployment and strong dynamic adaptive capabilities, asynchronous networks are widely used, and there are many studies on it.

Naveen and Kumar [28] studied the choice of duty cycle and relay node in low duty cycle networks. Their results suggest that the relationship between the duty cycle and delay of a node is: when duty cycle is larger, its delay is smaller and the energy consumption of the node is greater. This is because the greater the duty cycle of the node is, the longer the node stays in awake. Therefore, the probability that the receiver is in awake when the sender needs to send data is greater. Thus, the delay will be reduced. On the other hand, the greater the density of nodes, the more the forwarding nodes and the smaller their delays. At this time, when the SFNS increases, the probability that there is a receiver is in awake is greater when the sender has data to send. Thus, the delay will be reduced. In particular, Naveen and Kumar [28] also gives a way to control SFNS to reduce delay. Although the number of SFNS is higher, the higher the probability that the sender finds an awake receiver, the smaller the delay,this does not mean that the delay of the entire data route is reduced. In fact, there are still more complicated relationships in the entire data route. When there is a packet to be sent, it would be better to select the node closest to the sink in the FNS as the relay node for packet forwarding. In this way, in the routing process, each hop of the data route advances to the sink with the largest distance, so the packet requires fewer hops to reach the sink. Therefore, at this time, the delay of the data routing is relatively small. Conversely, if the node farther away from the sink in the FNS is selected for data forwarding, the forward distance of each hop would be smaller, and thus more hops are needed to transmit data, which results in a larger delay. However, it is not an easy task for the sender to select the node closest to the sink in the FNS. This is because: when the sender has a packet to send, the node closest to the sink in the FNS may be in a sleep state. At this time, the sender has two choices: one is to wait for the node closest to the sink to switch to the awake state and then select it as a relay node to forward data. But at this time, the sender needs to wait thereby increasing the delay. Second choice is that the sender selects the node closest to the sink in the awake state in the FNS as relay node to perform data transmission. In this way, although the sender does not need to wait, the distance of the hop of the relay node towards the sink may be smaller, thereby increasing the number of hops. Therefore, the delay is not necessarily small. Naveen and Kumar [28] proposed a method to limit FNS to optimize network performance for the situation above. The method is to narrow the scope of the FNS. Only the nodes that make the one-hop route distance from the sender to the sink greater than r_0 are selected as the candidate nodes of the sender's relay node. And the nodes that make the advance distance from sender to sink less than r_0 are no longer in the FNS. In this way, the advance distance of one hop from the sender to the relay node towards the sink which is chosen from the narrowed FNS must be greater than r_0. Therefore, the wait time and the advance distance of the sender are both taken into account. However, these studies are mainly for the low duty cycle network, and the collision of nodes are not considered. Thus, the conclusions obtained cannot be applied to general networks. Moreover, these studies do not theoretically give an optimal relationship between SFNS and duty cycle so these studies are usually based on some empirical values to design and optimize the network, which is not suitable for the universal network.

Other studies similar to the above can be found in [29]. The study of feedback control delay by adjusting the duty cycle of nodes can be seen in [57]. Similarly, their study is based on the idea reducing the delay by increasing the duty cycle of the nodes. And the adopted method is feedback control. The specific idea is: When the delay of the data packet received by the sink exceeds the predetermined threshold, then the duty cycle of the node needs to be increased to reduce the delay. Conversely, if the delay of the data packet received by the sink is less than the predetermined threshold, then the duty cycle of the node needs to be reduced to save energy. And the feedback control method is: when the difference between the end to end delay and the predetermined threshold exceeds the set value, the message packet of the adjustment duty cycle is sent along the reverse path of the data route. After receiving the message packet, the nodes are proportionally increased (or reduced) their own duty cycle, thus making the delay within the expected range. Chen *et al.* [58] also proposed a method of controlling delay by adjusting the duty cycle. The method they proposed is an improvement on the above method. The main improvement is: The adjustment on duty cycle of the node is not the same, but depends on the residual energy when the end to end delay exceeds the predetermined threshold. The increment of the duty cycle is bigger when the node has more residual energy. The increment of the duty cycle is smaller when the node has less residual energy. In the wireless sensor network, the node in the region far from the sink has fewer data to transmit, so there are a lot of residual energy. Therefore, the duty cycle of the far sink region node is large. Similarly, the residual energy of the node in the region near the sink is small, so the increment of the duty cycle is small. Thus, this method is able to balance the energy consumption of the network and improve the network life while reducing the end to end delay [58].

Optimizing delay by adjusting the duty cycle is an effective method, but the shortcoming of this method is that the increase of the duty cycle of will also increase the energy consumption of the node [58]. At the same time, it will increase the probability of node communication collision. As a result, multiple retransmissions of the data packet consume more energy, and the collision increases the delay. This indicates that the delay and energy consumption of the route are related to multiple factors. Adjusting the duty cycle is only a simplification of the problem, which is actually difficult to achieve optimal results [34].

In addition to the duty cycle, the adjustment of active slot can also control the delay. The main reason for the delay in the asynchronous wireless sensor network is that there are many sleep slots between the active slot of the adjacent nodes in the routing path, which results in a larger delay. If the active slots between nodes are continuous, data routing can be forwarded through consecutive slots, thus reducing delay. The advantage of this method is that only the active slot of the node needs to be adjusted, while duty cycle is not increased. Therefore, the delay could be reduced without increasing the energy consumption of the network. From this point, it is also an effective method to reduce delay. Teng *et al.* [18] proposed a local synchronization method for reducing delay. In their method, each node selects a small number of nodes closest to the sink from all FNSs to form a synchronized FNS. Each node actively synchronizes with the nodes in the synchronous FNS. The advantage of this method is that: the data of sender can be sent without waiting or waiting for a few time, which reduces the delay. Of course, the system needs to pay the cost of local synchronization. However, this synchronization does not require as strong a synchronization as the synchronization network over the entire network. In their approach, only a local synchronization between the sender and the corresponding FNS is required. The cost of synchronization is relatively small.

The network discussed above is all based on the assumption that there is no data loss in wireless transmission. However, if considering a high packet loss rate in wireless communication, the data routing strategy will be very different. At this time, the energy consumption and delay of the network increase significantly due to the loss of data packets. For the network with data loss, the researchers also proposed the corresponding routing method. The simplest method is the Send and Wait Automatic Repeat-Request (SW-ARQ) protocol [59]. In the SW-ARQ protocol, the sender waits for the receiver to return an ACK after sending the packet. If the sender receives the ACK, it indicates that the packet has been successfully sent. If the sender does not receive the ACK of the receiver within the expected time, the sender will resend the packet which is called timeout retransmission. The above process continues until the sender receives the ACK which indicates that the data packet is successfully sent, or the number of timeout retransmissions exceeds the predetermined maximum number which means the transmission of the data packet is abandoned. From the above process, it can be seen that the network with higher packet loss rate of SW-ARQ will be larger. The delay, and energy consumption are also greater than the ideal communication network [59]. To reduce the delay of data routing in a network with loss rate, the opportunity route is proposed to reduce delay for loss WSNS [27], [34]. The main idea of opportunistic routing is: Sender selects a group of receivers to use the broadcast method for data transmission. In this way, as long as one of multiple receivers receives the data, the data packet transmission succeeds. Obviously, this method effectively improves the success rate of one-time transmission, which effectively reduces the delay. However, in such a method, the node transmits the data by using the broadcast transmission method, so multiple receivers may receive the data at the same time, which will increase the energy consumption of the data packet transmission. Moreover, when multiple receivers receive the data, the system have to make sure that only one node will be selected as the relay node to forward the route, and other receivers do not need to forward the route even if the data is successfully received, thus increasing the system cost of the routing protocol. The opportunity routing proposed by most researchers is mainly for non-duty cycle based WSNs. In such a network, since the node is always in the awake state, it is easy to select multiple receivers to use the broadcast method for data transmission. However, in the duty cycle based network, it is difficult to select multiple receivers at the same time [27]. Because these nodes are periodic sleep/awake, it is difficult for multiple receivers to be in the awake state at the same time. Xiang *et al.* [27] proposed an opportunity routing strategy for duty cycle based WSNs. The main idea of their method is to adjust the node's duty cycle to wake up a group of nodes with similar positions, so that sender can select a set of receiver nodes at the same time [27].

In sensor networks, transmission delay and energy consumption are important factors affecting network performance. How to reduce transmission delay and extend network lifetime are the key problems in sensor networks [2], [17], [27], [28], [34]. Although there are many studies on the WSNs, the research on the comprehensive optimization of duty cycle, SFNS, energy consumption and delay is rare, and few studies on the optimal relationship between them through theoretical analysis. Therefore, this paper attempts to integrate the above factors to optimize the network.

III. SYSDEM MODEL AND PROBLEM STATEMENTS

A. NETWORK MODEL

The network model adopted in this paper is similar to [28], [29]. As shown in Figure 1, a sensor network with radius R consists of a large number of sensor nodes and a sink node. The sink node is at the center of the WSN network. The other sensor nodes are evenly deployed in the network. N_i represents the i-th node in the sensor network, then the set of all sensor nodes in the network can be expressed as:

$$\mathbb{N} = \{N_1, N_2, \ldots, N_i, \ldots, N_m\}, \quad i \epsilon m$$

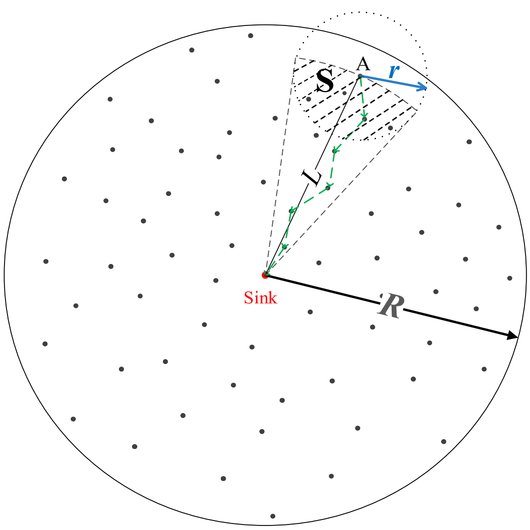

FIGURE 1. The model of the network.

When the network detects an anomaly, Sensor nodes near events send a packet to the node closer to sink, which is the center of the network, and eventually the packet is sent to the sink. The transmission radius of the source node A is r. Due to the transmission radius of a single node r is limited, so the transmission adopts a multi-hop mode. The peripheral node transmits the information to the node closer to the sink, and thus repeatedly transmits the information to the sink. The node within the transmission range of the source node closer to the sink than the source node is called a candidate node. The diagonal shaded part S is the candidate node area of node A. All of the candidate nodes are possible to be the forwarding node of node A. The node density is ρ, then the number of candidate nodes is $S \cdot \rho$. The green broken line in Figure 1 indicates a possible transmission path of node A.

Channel impairments exist in wireless communication environment. Various factors will affect the communication channel, such as geographic trend, wireless signal interference, magnetic field, obstacles and other factors, which may bring communication errors or other effects. However, the focus of this paper is the sender's waiting time. In order to facilitate the analysis of the problem, we simplify the system model. At the same time, because channel impairments have always existed, whether in the original case or in the case of the optimization of the proposed scheme, the impact of channel impairments is similar. So, this will not affect our performance analysis of the scheme in this paper.

B. RELATED DEFINITIONS AND ENERGY CONSUPTION MODLE

In order to save energy, the nodes in WSNs work in a duty cycle mode. The length of one cycle is $\mathbf{T}$. Time is divided into slots with a slot length of $\mathbf{T_a}$. There are $\boldsymbol{\tau}$ slots in one cycle, that is, $\mathbf{T} = \tau \mathbf{T_a}$. The node works only in one slot during each cycle. There is Eq. (1)

$$\tau = \frac{T}{T_a} \tag{1}$$

where T is the length of one cycle and T_a represents the active working slot.

Obviously, the duty cycle Ω is the ratio of the node's active working slot to the length of one cycle, as shown in Eq. (2).

$$\Omega = \frac{1}{\tau} \tag{2}$$

In the energy model of this paper, the energy consumption of nodes is mainly composed of the following components: (1) energy consumption of receiving packet (2) energy consumption of transmitting packet (3) energy consumption in sleep state (4) energy consumption in idle state. When the node is in working mode but does not send and receive packets, the node is in low power listening state.

The main parameters in this paper are shown in Table 1.

TABLE 1. Network parameters.

Symbol	Description	Value
T	The initial time of a cycle	100 ms
ω_r	The power used by a node to receive a packet;	303.6 mw
ω_t	The power used to transmit a packet	617.1 mw
ω_l	Reception power consumption	230 mw
τ	The number of time slot	Its specific value depends on different network conditions or is obtained by calculation
μ	The event generation probability	0.1
r	The node transmission radius	80 m
R	The network radius	500 m
r_0	The minimum one hop forward distance	It needs to be obtained by the algorithms according to the specific situation.
Ω	Duty cycle	It equals $1/_\tau$
t_{s_r}	Time to send or receive a packet	0.1ms
ohd	One hop forwarder distance	It is related to r_0 and needs to be calculated according to the situation.
$\mathbb{N}_R^L$	Number of received packets	It is related to network radius, distance and other variables, which need to be calculated based on these parameters.

C. PROBLEM STATEMENTS

When a node detects an event, it generates a data packet and sends it to the sink node by multi-hop routing, which will lead to delay. Therefore, in addition to exploring the optimal relationship among duty cycle, SFNS, data transmission delay and energy consumption, the research goal of this paper is to optimize the delay and energy efficiency by adjusting the duty cycle and the size of forwarding set of nodes. The main research objectives of this paper are as follows:

1) REDUCE THE END-TO-END DELAY

The end-to-end delay is the time from detected the event by a node and generates a data packet to the packet is transmitted to sink, which can be expressed as:

$$D = \sum_{j=1}^{k} d_j, \quad j \in [1, k] \tag{3}$$

where k is the number of hops. d_j represents the delay of the j-th hop. Then the total end-to-end delay is the sum of the delays of all hop.

2) IMPROVE THE ENERGY EFFICIENCY OF THE NETWORK

Energy efficiency is an important indicator of wireless sensor networks. Due to the data aggregation characteristics of wireless sensor networks, the closer to the sink node, the larger the data load and the faster the energy consumption. When nodes closer to the sink die, the nodes far from the sink still have a lot of energy. How to use residual energy effectively is the key to improve the performance of the network. As shown in formula (4), energy efficiency can be expressed as the ratio of the energy consumed by nodes in the network to the initial total energy of the network when the hot zone nodes die.

$$e = \frac{\sum_i^m E_{consumed}^i}{m \cdot E_{initial}} \tag{4}$$

where m is the number of sensor nodes in the network, $E_{consumed}^i$ represents the energy consumed by the i-th node when the network dies, and $E_{initial}$ represents the initial total energy of the battery of a single node.

How to adjust the node's duty cycle and the size of forwarding set to achieve the optimization of delay and energy efficiency is the research objectives of this paper.

$$\begin{cases} \min(D) = \min\left(\sum_{j=1}^{k} d_j\right), j \in [1, k] \\ \max(e) = \min\left(\dfrac{\sum_i^m E_{consumed}^i}{m \cdot E_{initial}}\right) \end{cases} \tag{5}$$

IV. THEORETICAL ANALYSIS OF NETWORK PARAMETER OPTIMIZATION

A. RESEARCH MOTIVATION

In a duty cycle network, all nodes wake up only once in a cycle, and stay active during the time of T_a. At other times, they are asleep. When sender has a data packet to send, its candidate forwarding nodes may be all asleep. Only when one of the candidate nodes wake up can the information be sent out. In low duty cycle or sparse network, the sender may have to wait for a long time before the candidate node wakes up, and wait time will become the main reason for delay. As shown in Figure 2, before sending a packet, the sender sends its preamble circularly. When P-Ack is received, the sender starts sending the packet until it receives an acknowledgement message from the forwarding node. Thus, the packet is successfully transmitted.

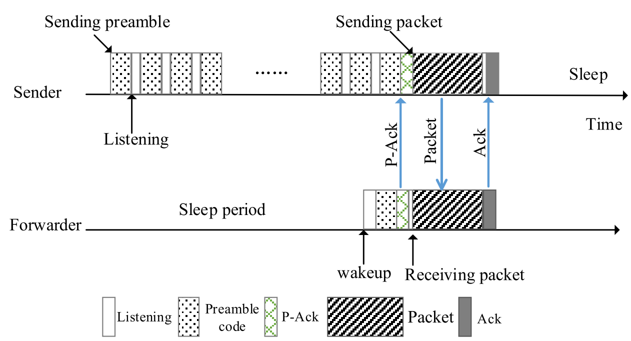

FIGURE 2. Duty cycle operating mode.

However, for a high duty cycle or dense network, there may be multiple candidate nodes in the awake state when the sender sends a packet. Although their distances from the sender are different, the propagation speed of the wireless signal is about 300,000 km/s, which is the speed of light propagation. In the network model of this paper, the node communication radius is only 80m, that is, the distance difference between multiple receivers is less than 80m. In this case, the influence of the time difference caused by the distance on the reception time can be ignored. In other words, when multiple receivers are awake, they receive the sender's packet and return an ACK to the sender. When that happens, the ACK messages from multiple receivers collides in the sender, that is ACK collision, as shown in Figure 3. In this time, the ACK message will not be received normally, causing the transmission to be unsuccessful, and the sender will continue to send packet. So, when computing delay, once ACK collision occurs, the sender will continue to send the packet in the next slot, which increases the waiting time by one slot. Thus, the more the collisions, the higher the delay. For dense networks, ACK collision is the main factor causing delay.

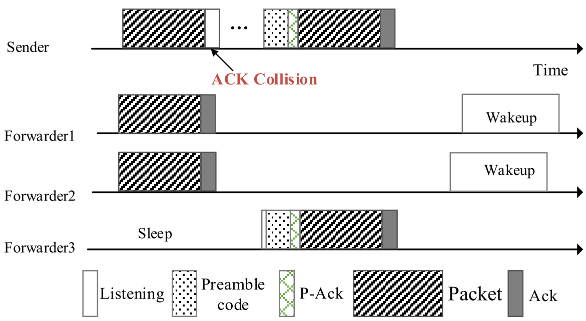

FIGURE 3. ACK collision.

In conclusion, when the sender has a packet to send, only one candidate node in the awake state can communicate successfully.

Figure 4 shows the end-to-end delay of different networks when $L = 500$m. In the network with $\tau = 20$ and $\rho = 0.007$,

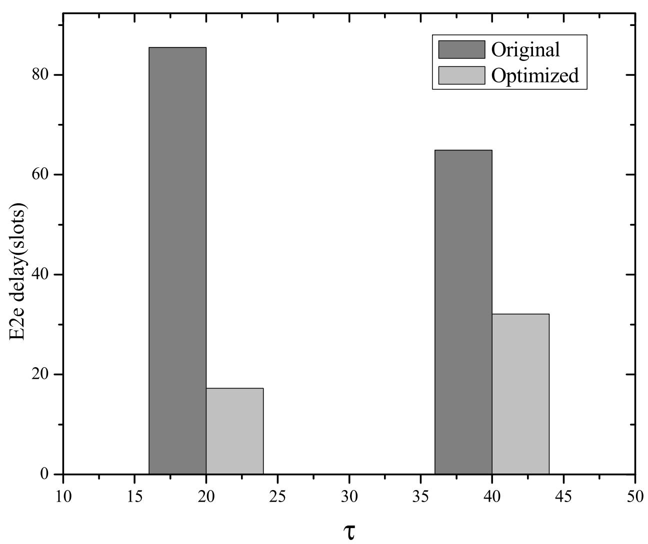

FIGURE 4. End-to-end delay in different networks.

the number of candidate nodes from near to far changes in the range of 55~68, and the value of η/τ is in the range of 2.75~3.4. In this time, the number of candidates is relatively too large or the duty cycle is relatively too large, resulting in a high delay due to the conflict. On the contrary, in the network with $\tau = 40$ and $\rho = 0.001$, the number of candidate nodes from near to far changes in the range of 8~10, and the value of η/τ is in the range of 0.2~0.25. At this time, the number of candidates is relatively too small or the duty cycle is relatively too little. Waiting for the wakeup of the candidate node at this time is the main factor causing the delay.

Figure 5 shows the energy consumption per unit time of node in the hot zone and 300m from sink in the above network. In the two networks mentioned above, the energy consumption at 300m is only 34.9% and 27.7% of the hot zone. At the end of the network life, there will be a lot of residual energy in the network.

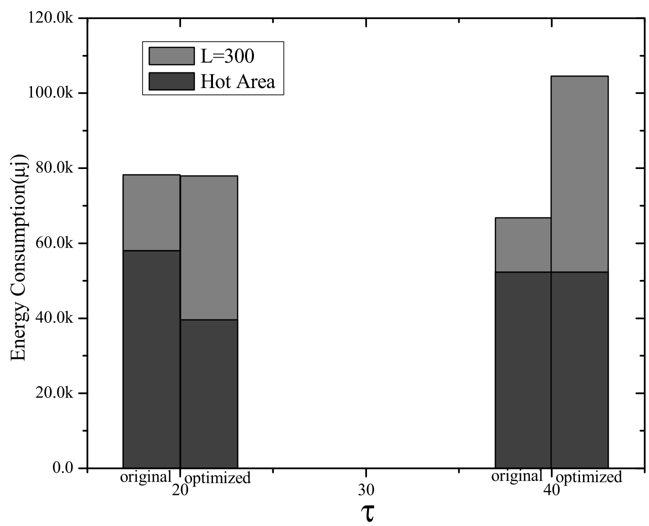

FIGURE 5. Energy consumption at different distances in different networks.

It can be found that too many or too few candidate nodes, too large or too small duty cycle, delay and energy efficiency will show very poor performance. We hope to reduce network delay without reducing network lifetime by optimizing existing strategies. Firstly, different optimization strategies are given for different networks. For sparse networks, increasing the number of nodes is often expensive or impossible. We consider using the residual energy in the far sink region to increase the duty cycle of nodes to reduce the delay and improve the energy efficiency of the network. For dense networks, the minimum forward distance of one hop is considered. Only when the candidate node makes the forward distance greater than a certain value $\mathbf{r_0}$, it is possible to be selected as the forward node. Finally, a comprehensive optimization strategy suitable for any network is obtained. After optimizing the network using the scheme proposed in this paper, the end-to-end delay is greatly reduced and the energy consumption in the far sink region is close to that in the hot zone, effectively improving the energy utilization rate. Figure 4 and Figure 5 respectively show the comparison of delay and energy consumption before and after optimization.

B. THE EXPECTATIONS OF DELAY AND NUMBER OF PACKETS RECEIVED

1) THE CALCULATION OF DELAY EXCEPTIONS

From the previous analysis, we know that if only one forwarding node wakes up in a slot when the sender sends data, the transmission succeeds, if no node wakes up or collisions occur because more than one node wakes up, the transmission is unsuccessful, and the sender will continue to be in the sending state until the transmission succeeds, causing delay and extra energy consumption. It can be seen that the delay of one hop mainly comes from waiting time and collision.

If the number of SFNS of a sender is n,and the length of a cycle is τ slots, and assume that the transmission stops automatically after a cycle, the mathematical expectation of a hop delay can be calculated according to the transmission model in this paper. Due to the above assumption, we require a higher probability of successful transmission in a cycle. In this paper, the model is only used when the probability of successful transmission is more than 90%. For the convenience of calculation, $p_\tau^n(i)$ is defined as the probability of successful transmission in the i-th slot when sender has n candidate forwards and a cycle has τ slots. That is to say, the transmission is unsuccessful in $1 \sim i-1$ slot, and only one node wakes up in the i-th slot.

Theorem 1: When a cycle has τ slots and the sender has n candidate nodes, the probability of successful transmission in the i-th slot is as follows:

$$p_\tau^n(i) = \sum_{v=1}^{\Gamma} (-1)^{v-1} \cdot C_{i-1}^{v-1} \cdot C_n^m \cdot v! \cdot \left(\frac{1}{\tau}\right)^v \cdot \left(1-\frac{v}{\tau}\right)^{n-v} \tag{6}$$

where $\Gamma = min(i, n)$.

The mathematical expectation of one hop delay is

$$D = \frac{\sum_{i=1}^{\tau} i \cdot p_\tau^n(i)}{\sum_{i=1}^{\tau} p_\tau^n(i)} \tag{7}$$

Proof: For the convenience of proof, $q_\tau^n(v)$ is defined as the probability of the event that only one node wakes up in v slots out of τ slots. It can be expressed as

$$q_\tau^n(v) = C_n^v \cdot v! \cdot \left(\frac{1}{\tau}\right)^v \cdot \left(1-\frac{v}{\tau}\right)^{n-v} \tag{8}$$

Then, the probability that only one node wakes up in a certain slot is expressed as

$$q_\tau^n(1) = C_n^1 \cdot \left(\frac{1}{\tau}\right) \cdot \left(1-\frac{1}{\tau}\right)^{n-1} \tag{9}$$

Obviously, $p_\tau^n(1) = q_\tau^n(1)$.

E_j is defined as an event in which j-th slot and i-th slot each has one candidate node wake-up. Then there is

$$p_\tau^n(i) = q_\tau^n(1) - p\left(\cup E_j\right) \quad 1 \le j < i \tag{10}$$

From the Mutual Exclusion Theorem, we obtain:

$$\begin{aligned} p\left(\cup E_j\right) &= \sum_j p\left(E_j\right) - \sum_{j<} \sum_l p\left(E_j E_l\right) \\ &\quad + \sum_{j<} \sum_{l<} \sum_r p\left(E_j E_l E_r\right) \\ &\quad - \cdots + (-1)^i p\left(E_1 E_2 \cdot \cdots \cdot E_{i-1}\right) \end{aligned} \tag{11}$$

For all $1 \le j < i$,

$$p\left(E_j\right) = q_\tau^n(2) \tag{12}$$

Also, we can obtain

$$p\left(E_{j_1} E_{j_2} \cdots E_{j_r}\right) = q_\tau^n(r+1) \tag{13}$$

Then,

$$\begin{aligned} &p_\tau^n(i) \\ &= q_\tau^n(1) - \left[C_{i-1}^1 \cdot q_\tau^n(2) - C_{i-1}^2 \cdot q_\tau^n(3) + \cdots + (-1)^i \cdot C_{i-1}^{i-1} \cdot q_\tau^n(i)\right] \\ &= \sum_{v=1}^{i} (-1)^{v-1} \cdot C_{i-1}^{v-1} \cdot q_\tau^n(v) \\ &= \sum_{v=1}^{i} (-1)^{v-1} \cdot C_{i-1}^{v-1} \cdot {}_n^m \cdot v! \cdot \left(\frac{1}{\tau}\right)^v \cdot \left(1-\frac{v}{\tau}\right)^{n-v} \\ &\qquad 1 \le i \le \tau \end{aligned} \tag{14}$$

When $v > n$, $q_\tau^n(v) = 0$, so formula (14) can be written as follows

$$p_\tau^n(i) = \sum_{v=1}^{\Gamma} (-1)^{v-1} \cdot C_{i-1}^{v-1} \cdot C_n^m \cdot v! \cdot \left(\frac{1}{\tau}\right)^v \cdot \left(1-\frac{v}{\tau}\right)^{n-v} \tag{15}$$

where $\Gamma = min(i, n)$.

At the same time, the probability of successful transmission in a cycle can be obtained as shown in Formula (16).

$$p_{sucess}^{n,\tau} = \sum_{i=1}^{\tau} p_\tau^n(i) \tag{16}$$

Figure 6 and Figure 7 show the influence of τ and n on the probability of transmission success respectively. It can be seen that the value of τ cannot be too small. This is because

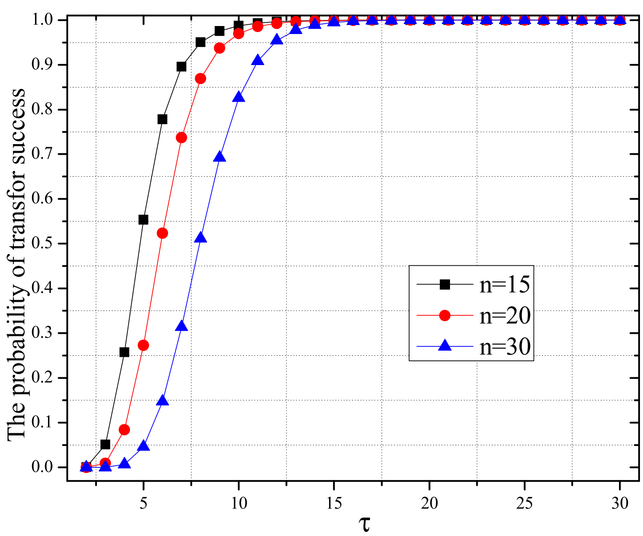

FIGURE 6. The probability of transmission success varies with τ.

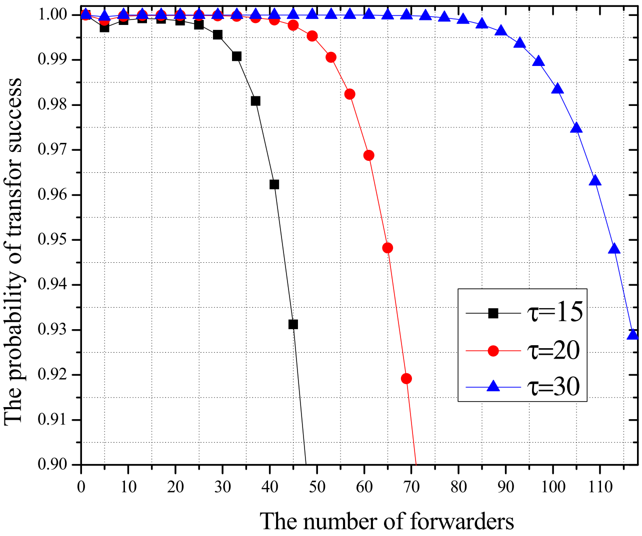

FIGURE 7. The probability of transmission success varies with ***n***.

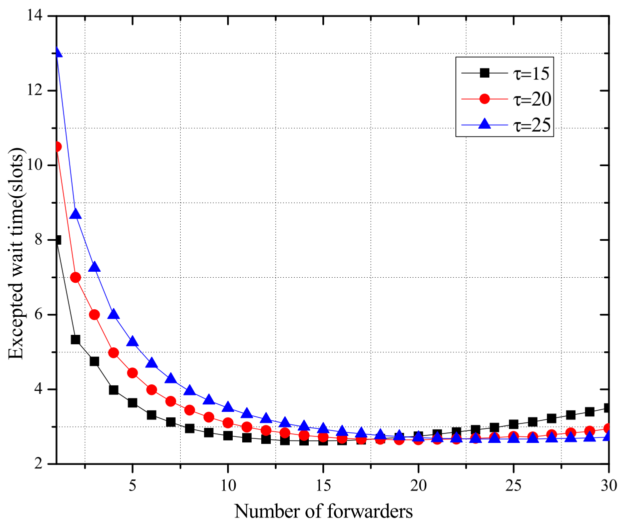

FIGURE 8. The expected sender wait time varies with ***n***.

all nodes will wake up in a certain slot per cycle. Due to the slot model is adopted, when the number of slots is too small, the probability of waking up of more than one candidate node in the same slot will increase, that is, the probability of collision will increase which will reduce the probability of successful transmission in a cycle. So it can be found in Figure 6 that the probability of successful transmission increases with the increase of τ. Similarly, increasing n increases the probability of collision. As shown in Figure 7, the probability of successful transmission decreases with the increase of n. For example, in a network with $\tau = 15$ and $n = 50$, the probability of successful transmission in a cycle is less than 90%. This situation will be fully taken into account in subsequent discussion.

Expected waiting time can be obtained from formula (7). Figure 8 shows the variation of delay with n after given τ. When the number of candidate nodes n is less than τ, the waiting time decreases rapidly with the increase of n, and the minimum value is obtained when the number of candidate nodes n is equal to τ. Figure 9 shows the variation of expected delay with τ after given n. It can be seen that the number of candidate nodes n and duty cycle $1/\tau$ have similar effects on expected delay. The reason is that when waiting for the wakeup of the candidate node to become the main factor of the delay, increasing n will increase the probability that the candidate node is in the awake state in the same slot, and increasing the duty cycle has the same effect. When there are too many candidate nodes or the duty cycle $1/\tau$ is too large, the candidate node collision becomes the main factor of delay.

Besides, it can be noted that in Figure 9, corresponding to $n = 15, 20, 25$, the delay is minimized at $\tau = 15, 20, 25$. It can be found that for the three values of n, the delay is minimized when $n = \tau$.

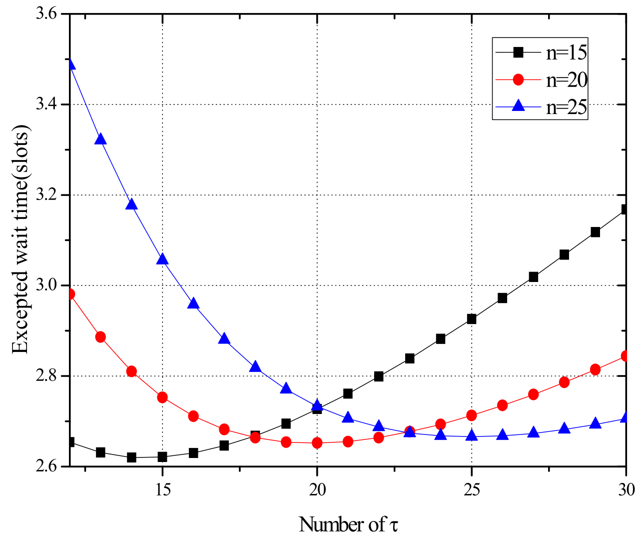

FIGURE 9. The expected sender wait time varies with τ.

2) EXCEPTED NUMBER OF PACKETS RECEIVED

Due to multiple candidate nodes will receive the sender's data packet in each collision. When sender sends a packet, it may be received many times. Next, we calculate the expected number of times the packet is received in each cycle

Theorem 2: When the sender has n candidate nodes, and there are τ slots per cycle, the expected number of times the same packet is received after the end of a cycle is recorded as $\ell(n, \tau)$. The probability that only one node wakes up in the i-th slot and j nodes wake up in the $1 \sim i-1$ slot is recorded as $\psi_n^\tau(i, j)$. $\mathcal{L}(i-1, j)$ is used to represent the probability that j nodes wake up in $1 \sim i-1$ slot but the transmission is unsuccessful. $\ell(n, \tau)$ can be obtained by the following formula

$$\ell(n, \tau) = \left\{ \sum_{i=2}^{\tau} \sum_{j=0}^{n-1} \left[(j+1) \cdot \psi_n^\tau(i, j) \cdot \mathcal{L}(i-1, j) \right] \right\} + 1 \cdot \mathrm{p}_\tau^\mathrm{n}(1) + n \cdot \mathcal{L}(n, \tau). \quad (17)$$

Proof: Obviously, the probability that only one node wakes up in the i-th slot and j nodes wake up in the $1 \sim i-1$ slot can be expressed as

$$\psi_n^\tau(i,j) = C_n^j \cdot C_{n-j}^1 \cdot \left(\frac{i-1}{\tau}\right)^j \cdot \left(\frac{1}{\tau}\right) \cdot \left(\frac{i-1}{\tau}\right)^{n-j-1} \tag{18}$$

where, $2 \le i \le \tau, 0 \le j \le n-1$.

According to theorem 1, when there are j nodes waking up in $1 \sim i-1$ slot, the probability of successful transmission is $p_{sucess}^{j,i-1} = \sum_{k=1}^{j} p_{i-1}^j(k)$, so the probability of transmission failure is

$$\mathcal{L}(i-1,j) = 1 - \sum_{k=1}^{j} p_{i-1}^j(k) \tag{19}$$

Then $\psi_n^\tau(i,j) \cdot L(i-1,j)$ is the probability of transmission succeed in the i-th slot when there are j nodes wake up in the $1 \sim i-1$ slot.In this time, $(j+1)$ packets are received,then the mathematical expectation of expected number of packets received is $(j+1) \cdot \psi_n^\tau(i,j) \cdot \mathcal{L}(i-1,j)$. The probability of successful transmission in the first slot is $p_\tau^n(1)$, when only one packet is received, so the mathematical expectation of expected number of packets received is $1 \cdot p_\tau^n(1)$, If the transmission is unsuccessful after a cycle, the mathematical expectation of expected number of packets received is $n \cdot L(n,\tau)$. Through the above analysis and calculation,we get this formula

$$\ell(n,\tau) = \left\{\sum_{i=2}^{\tau}\sum_{j=0}^{n-1}\left[(j+1)\cdot\psi_n^\tau(i,j)\cdot\mathcal{L}(i-1,j)\right]\right\} + p_\tau^n(1) + n\cdot\mathcal{L}(n,\tau).$$

The theorem is proved.

It can be seen from Figure 10, when $n = 1$, no matter what the value of τ is, the data packet is received only once, because there is only one node waking up in one cycle, and there will be no re-packet. With the increase of n, the probability of collision is higher and higher, and the expected

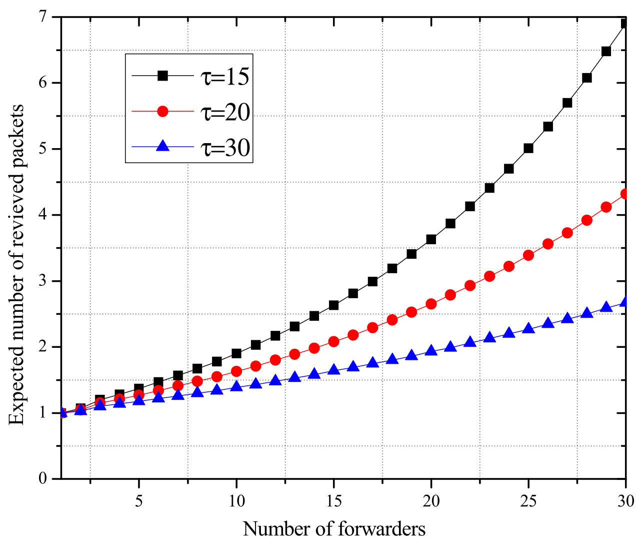

FIGURE 10. Expected number of packets received per transmission with the varies of *n*.

number of times the same packet is received is also more and more.

Figure 11 shows how the expected number of times a packet is received varies with the number of slots per cycle τ. With the increase of τ, that means, the duty cycle is getting smaller and smaller, the probability of multiple candidate nodes waking up in the same slot decreases, which reduces the probability of collision and the expectation of packet being received repeatedly.

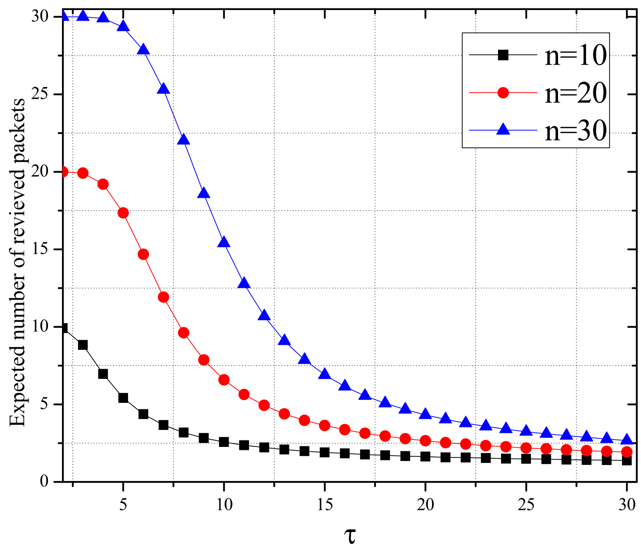

FIGURE 11. Expected number of packets received per transmission with the varies of τ.

C. CONCLUSION OF PARAMETER OPTIMITION

In the discussion in the previous section, it is found that the minimum delay is achieved at $n = \tau$, as shown in Figure 5 and Figure 6, and the reasons are explained in Figure 12 and Figure 13. When $n = 1$, the probability of successful transmission in each slot is $\frac{1}{\tau}$, and the expected delay time is $\frac{1}{\tau} \cdot \sum_{i=1}^{\tau} i$. If the probability of successful transmission is increased when i is smaller, such as $i = 1, 2$, and decrease the probability of successful transmission when i is larger, such as $i = \tau, \tau - 1$, the transmission delay will obviously be reduced.

In Figure 12, the initial condition of the network is $n = 1$ and $\tau = 20$. With the increase of n, $p(i)$ increases gradually when $i \le 5$, that is to say, the probability of successful transmission becomes larger and larger when $i \le 5$. And $p(i)$ decreases gradually when $i > 5$, then the probability of successful transmission becomes smaller and smaller when $i > 5$. Therefore, in the case of $n < \tau$, the expected delay decreases with the increase of n. However, in the case of $n > \tau$, the expected delay has the opposite vary with the increase of n. In Figure 13, with the increase of n, $p(i)$ decreases gradually when $i \le 4$, and $p(i)$ increases gradually when $i \ge 4$. When $n = 100$, the probability of successful transmission in each slot tends to be equal again, and the expected delay increases with the increase of n.

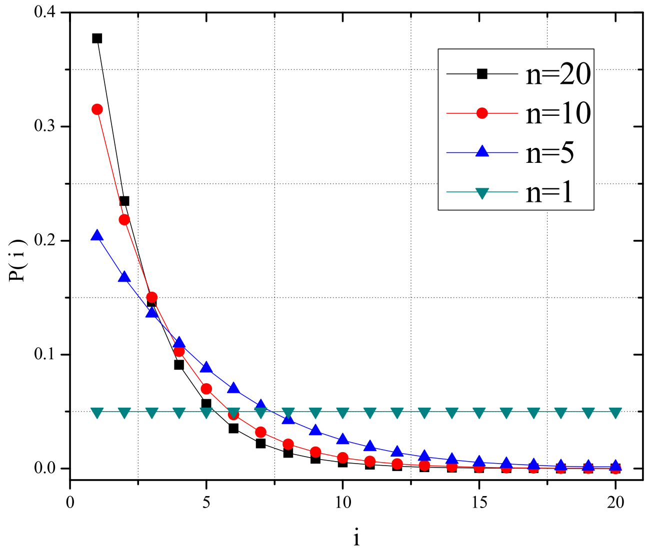

FIGURE 12. The probability of successful transmission in the *i*-th slot when $\tau = 20$.

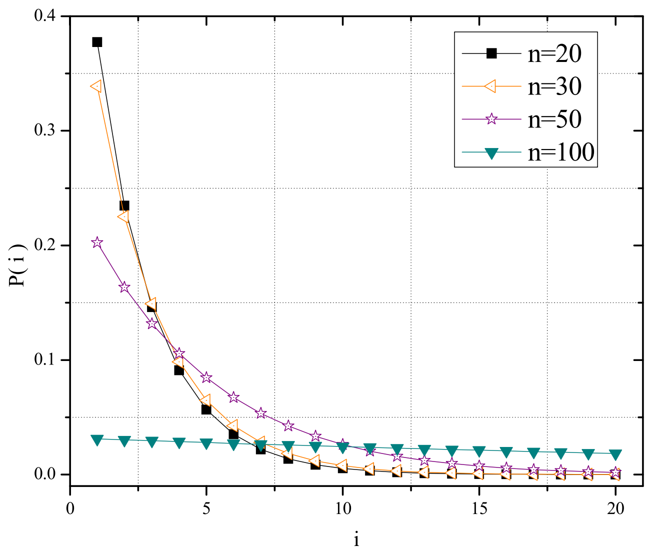

FIGURE 13. The probability of successful transmission in the *i*-th slot when $\tau = 20$.

In Figure 14 shows the expected delay of one hop corresponding to the value of n in Figure 12 and Figure 13. As in the analysis of probability distributions in Figure 12 and Figure 13, When $n < \tau$, the expected delay of one hop decreases with the increase of n, and when $n > \tau$, the expected delay of one hop increases with the increase of n, and get the minimum value when $n = \tau$.

In this paper, the way to reduce delay is to make $n = \tau$ in any networks as much as possible. For networks with ${}^{n}\!/_{\tau} > 1$, we consider reducing the number of candidate nodes n by setting the minimum one hop forward distance r_0. Candidate nodes are the nodes in Forwarding Node Set (FNS) of the sender. And for networks with ${}^{n}\!/_{\tau} < 1$, we consider increasing the duty cycle of nodes, that is to say, reducing τ.

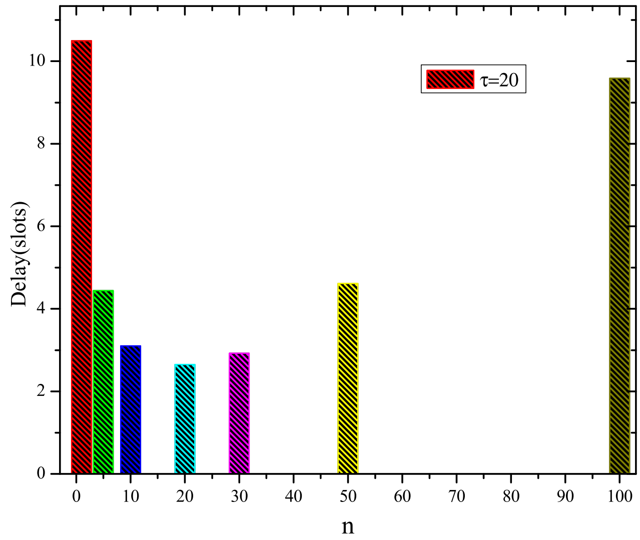

FIGURE 14. The expected delay with different values of *n* when $\tau = 20$.

V. THE DESIGN OF ODC-SFNS

Before introducing the scheme in this paper, the calculation methods of some important parameters and their changing rules are given first.

A. THE CALCULATION OF IMPORTANT PARAMETERS

1) LOAD CALCULATION

According to the network characteristics of this paper, combined with previous research,the WSNs with radius R, the load capacity of nodes far from sink Lm is

$$\mathbb{N}_R^L = m + 1 + \frac{m \cdot (m+1) \cdot ohd}{2 \cdot L} \tag{20}$$

where m is the integer that makes $L + m \cdot ohd$ is just less than R, and ohd is the expected one hop forward distance.

Figure 15 shows the variation of the load with the distance Lm. It can be found that the load decreases with the increase of the distance and decreases with the increase of

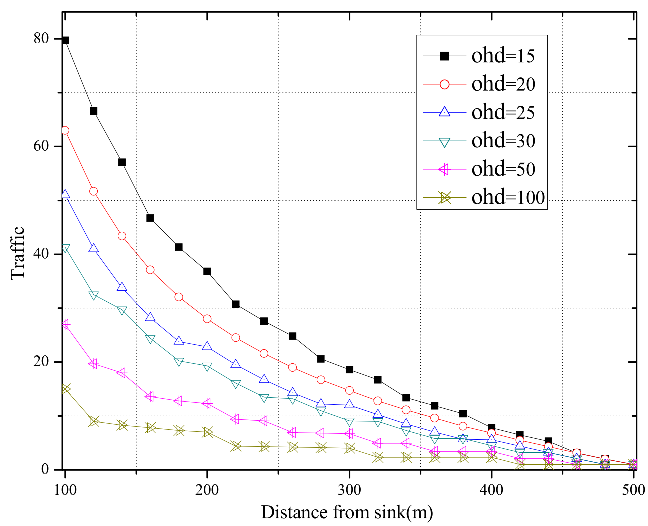

FIGURE 15. Load at different distance (r = 80).

ohd as a whole. That is to say, the closer to the sink, the larger the load, the farther the distance is, the smaller the load is.

2) CALCULATION OF CANDIDATE NODES' AREA AND NUMBER OF CANDIDATE NODES

In this paper, the nodes are evenly distributed in the network. Once the network is deployed, the density of the node distribution is a certain value, expressed by ρ. The product of the density and the area of the candidate nodes region is the number of candidate nodes.

Firstly, we calculate the area of candidate nodes. Within the sender's transmission radius, the nodes closer to the sink than the sender are the candidate nodes of the sender, also known as the candidate relay nodes or the candidate forwarding nodes. If the transmission radius of the sender is r and the distance of the sender A from the sink is Lm, the distribution area of the forwarders of the sender A is as shown in Figure 16.

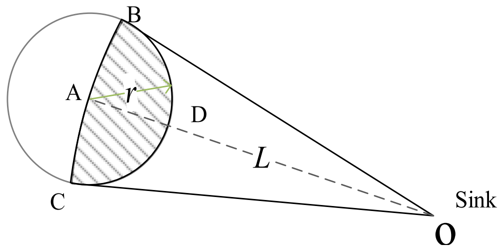

FIGURE 16. The candidate nodes' region.

It can be found in Figure 16 that the candidate nodes of sender A are distributed in the shadow area of the intersection of circle A and circle O. The area of this part is the sum of the area of sector BAC and sector BOC, minus the area of square OBAC, that is:

$$S_L = L^2 \cdot \theta + r^2 \cdot \vartheta - L \cdot r \cdot \sin(\theta) \tag{21}$$

where, $\theta = cos^{-1}\left(1 - \frac{r^2}{2L^2}\right)$, $\vartheta = cos^{-1}\left(\frac{r}{2L}\right)$.

Thus, the number of candidate nodes in the network with node density of ρ can be calculated, as shown in Figure 17.

As can be seen from Figure 17, the larger the density of nodes, the more the number of candidate nodes. With the same node density, the farther away from sink, the more candidate nodes, which is because the area of candidate nodes region increases with the increase of distance.

In the last part of Chapter 4, we mentioned setting r_0 to reduce the number of candidate nodes.r_0 is the minimum forward distance of one hop, that is, only when the distance between the node and sink is less than $(L - r_0)$m, it may be selected as a relay node. Thus, a node whose distance from sink is less than Lm but larger than $(L - r_0)$m is no longer a candidate node for sender. Next, we give a formula for calculating the area of candidate nodes after setting r_0.

If a packet is forwarded only if the forward distance is greater than r_0, the candidate node area is reduced to the shaded portion shown in Figure 18.

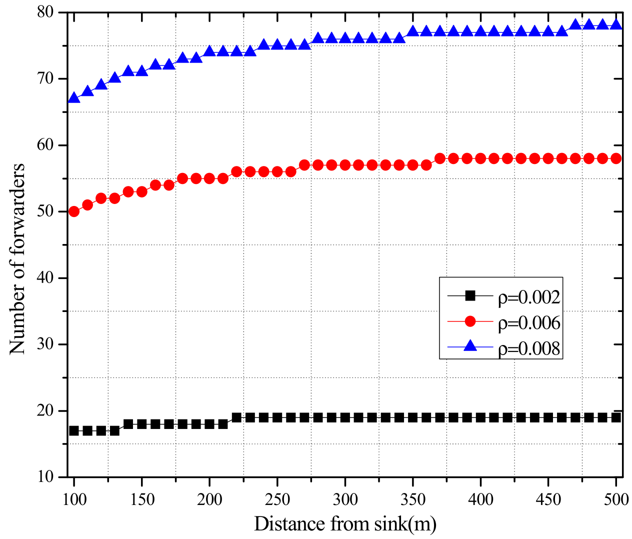

FIGURE 17. The number of forwarders VS distance from sink.

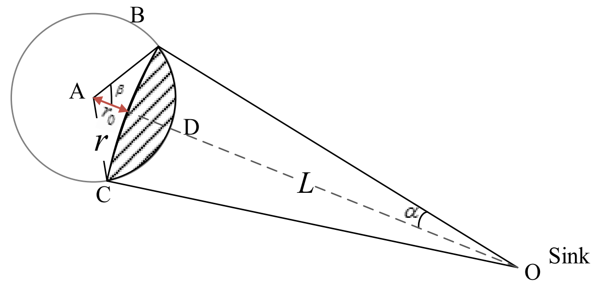

FIGURE 18. The candidate node region after r_0 is set.

Similar to the previous calculation method, the area calculation formula for the shaded part in Figure 18 is as follows:

$$S_L^{r_0} = (L - r_0)^2 \cdot \alpha + r^2 \cdot \beta - L \cdot r \cdot sin(\beta) \tag{22}$$

where,

$$\alpha = cos^{-1}\left(\frac{L^2 + (L - r_0)^2 - r^2}{2 \cdot L \cdot (L - r_0)}\right),$$

$$\beta = cos^{-1}\left(\frac{r^2 + L^2 - (L - r_0)^2}{2 \cdot r \cdot L}\right)$$

Obviously, formula (21) is the case of $r_0 = 0$ in formula (22).

The number of candidate nodes at this time is

$$n = \rho \cdot S_L^{r_0} \tag{23}$$

From formulas (22) and (23), we can get the area of candidate nodes region and the number of candidate nodes vary with r_0, as shown in Figure 19 and Figure 20.

It can be found that, with the increase of r_0, the area of candidate nodes decreases dramatically, and the number of candidate nodes decreases with the decrease of area. As shown in Figure 20, when $r_0 = 40$m, the number of candidate nodes

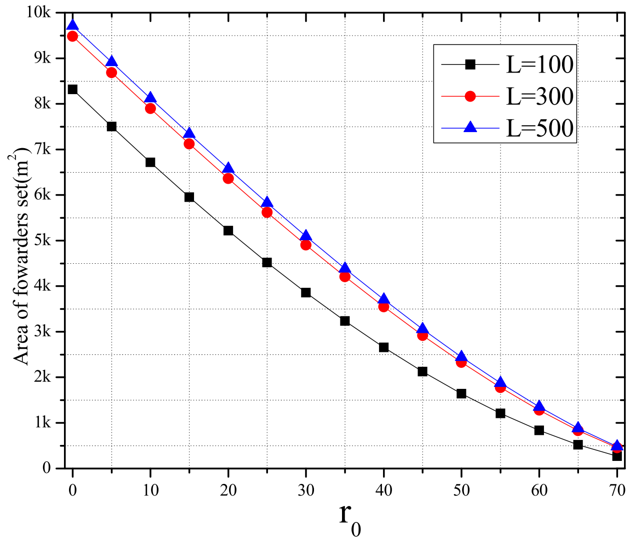

FIGURE 19. The area of the candidate node region varies with r_0.

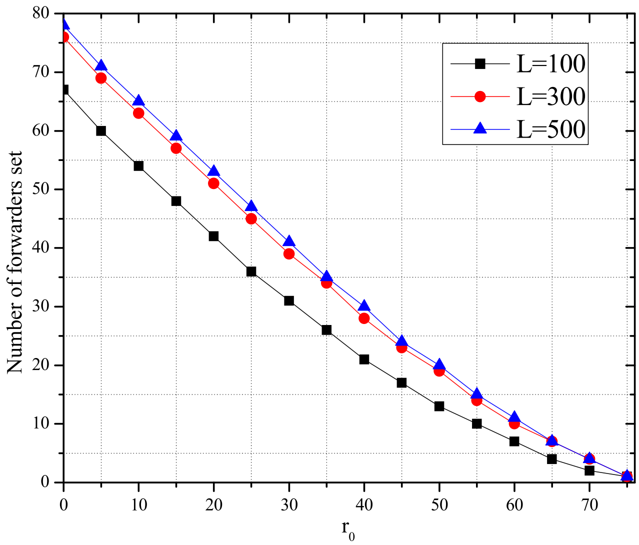

FIGURE 20. The number of candidate nodes varies with r_0 when $\rho = 0.008$.

at 300m from sink decreases from 76 to 28, which decreases by 63.1%. For dense networks, this will dramatically reduce the probability of collisions.

Figure 21 shows the number of times the packet is expected to be received varies with r_0 in the network with $\rho = 0.008, \tau = 20$. When $r_0 = 40$ m, the number of times the packet is expected to be received at $L = 300$ m is only 10.8% of the original.

(3) Calculation of Expected Delay of One Hop

The number of candidate nodes can be obtained by formula (22) and formula (23). Combining with theorem 1, the expected delay of one hop can be obtained after the number of slots per cycle is given.

Theorem 3: If the node density of the network is ρ and the number of slots per cycle is τ, then the delay of one hop at

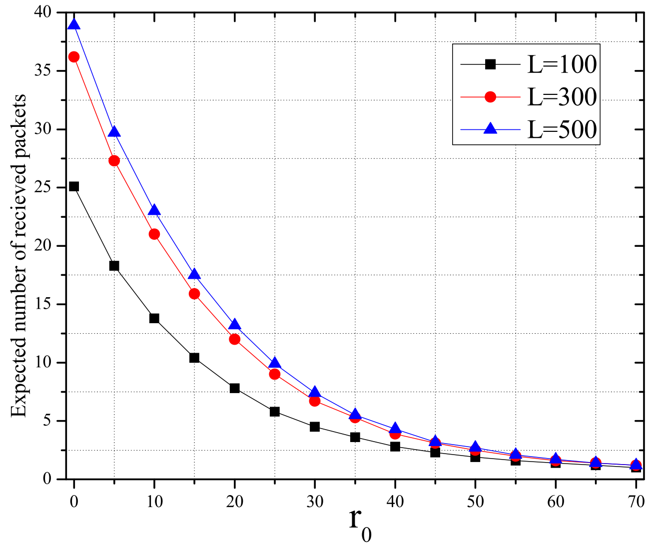

FIGURE 21. The number of times the packet is expected to be received varies with r_0 ($\rho = 0.008$, $\tau = 20$).

the distance Lm from sink of the network is:

$$D_\tau^{r_0} = \frac{\sum_{i=1}^{\tau} i \cdot \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{\rho S_L^{r_0}-\nu}\right]\right\}}{\sum_{i=1}^{\tau} \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{\rho S_L^{r_0}-\nu}\right]\right\}} \tag{24}$$

where, $S_L^{r_0}$ as shown in formula (22), $\Gamma = min\left(i, \rho \cdot S_L^{r_0}\right)$.

Proof: From formula (6) and formula (7), it can be obtained:

$$D_\tau^{n} = \frac{\sum_{i=1}^{\tau} i \cdot \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{n-\nu}\right]\right\}}{\sum_{i=1}^{\tau} \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{n-\nu}\right]\right\}} \tag{25}$$

where $\Gamma = min\,(i, n)$.

Due to $n = \rho \cdot S_L^{r_0}$, then the upper form can be written as follows

$$D_\tau^{r_0} = \frac{\sum_{i=1}^{\tau} i \cdot \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{\rho S_L^{r_0}-\nu}\right]\right\}}{\sum_{i=1}^{\tau} \sum_{\nu=1}^{\Gamma} \left\{(-1)^{\nu-1} C_{i-1}^{\nu-1} \cdot \left[C_n^{\nu} \cdot \nu! \cdot \left(\frac{1}{\tau}\right)^{\nu} \cdot \left(1-\frac{\nu}{\tau}\right)^{\rho S_L^{r_0}-\nu}\right]\right\}} \tag{26}$$

where, $S_L^{r_0}$ as shown in formula (22), $\Gamma = min\left(i, \rho \cdot S_L^{r_0}\right)$

If the number of slots per cycle $\tau = 20$, the expected delay of one hop can be obtained by formula (24), as shown in Figure 22.

In Figure 22, with the increase of r_0, the excepted delay of one hop decreases first and then increases. At $L = 300$m, the delay of one hop gain the minimum value at r_0 =50m, and

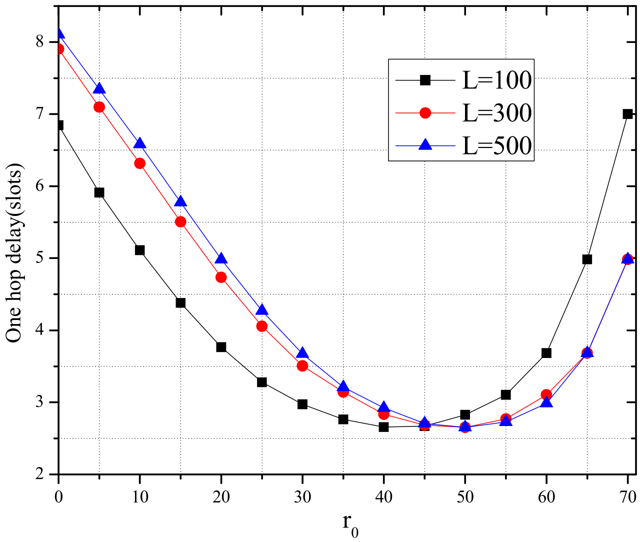

FIGURE 22. One hop delay VS r_0 ($\rho = 0.008$, $\tau = 20$).

the delay decreases by about 66.6%. It can be seen that when the number of candidate nodes is much larger than the number of slots, increasing r_0 can significantly reduce the one hop delay. This is because increasing r_0 can reduce n and make n approach τ gradually. But after getting the minimum value, continue to increase r_0 will make n less than τ. At this time, the sender's waiting time for the forwarding node to wake up becomes the main factor of the one hop delay. Therefore, with the increase of r_0, the delay also increases. Choosing the appropriate value of r_0 is very important for optimizing the delay.

(4) The Calculation of One Hop Forward Distance

If the distance from the sender to the sink is Lm, and the distance from the relay node that successfully completes communication with the sender is L'm, then $\left(L - L'\right)$ is the one hop forward distance.

When the distance between sender and sink is Lm, the transmission radius of nodes is r, and the minimum one hop forward distance is r_0,since the nodes are evenly distributed, the probability that the forward distance of one hop is x is:

$$f\left(x\right) = \frac{2\left(L-x\right)}{S_L^{r_0}} cos^{-1}\left[\frac{L^2+\left(L-x\right)^2-r^2}{2L\text{ (L-x)}}\right] \quad (27)$$

The range of x is $[r_0, r]$, then the exception of one hop forward distance is

$$ohd = \int_{r_0}^{r} x \cdot f(x)dx \quad (28)$$

Thus, combine formula (20) with formula (28), the load can be expressed as

$$\mathbb{N}_R^L = m + 1 + \frac{m \cdot (m+1) \cdot \int_{r_0}^{r} x \cdot f(x)dx}{2 \cdot L} \quad (29)$$

where m is an integer that makes $L + m \cdot \int_{r_0}^{r} x \cdot f(x)dx$ is just less than R.

It can be seen from Figure 23 that the one-hop forward distance increases significantly with the increase of r_0. Each hop on the path will be transmitted farther, and the number of hops from the source node to the sink may be reduced accordingly. The reduction in the number of hops will dramatically reduce the end-to-end delay. Figure 24 shows the load varies with r_0. We find that increasing r_0 can reduce the load carried by the node. At the distance of $L=$ 300m, when $r_0 = 40$m, the load is only 54.8% of the original. Since the energy consumption of a node is positively related to the load, increasing r_0 will reduce the energy consumption of nodes.

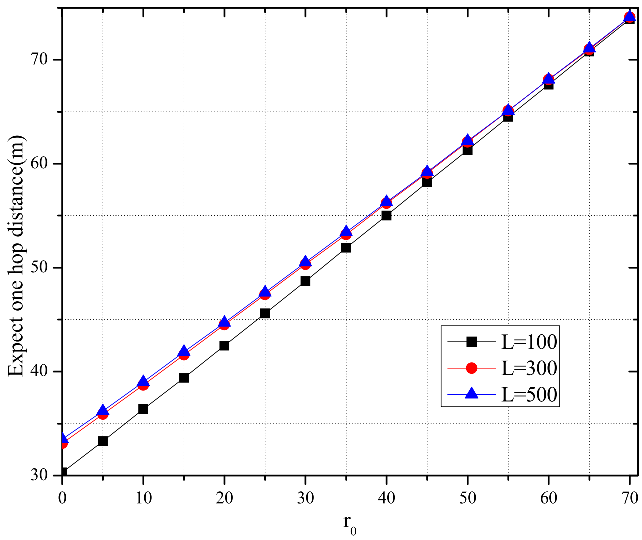

FIGURE 23. One hop forward distance varies with r_0.

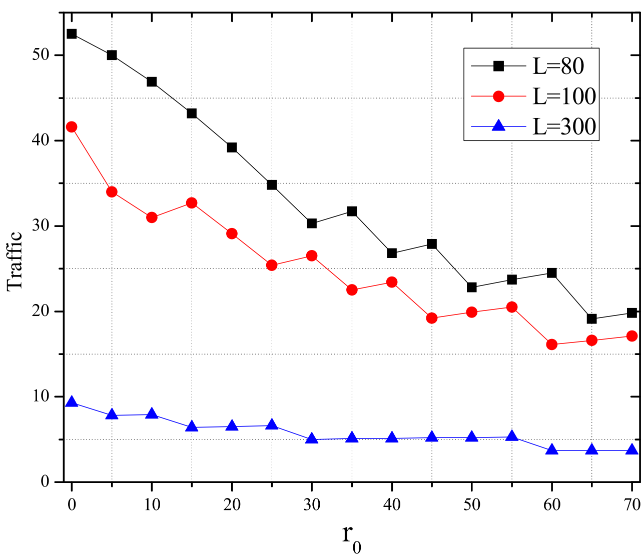

FIGURE 24. The load varies with r_0.

Algorithm 1 is the method of obtaining the number of hops. When calculating the number of hops, due to the strong communication ability of sink, we think that only sink is in their FNS of nodes whose distance from sink is less than r from sink. When the packet is transmitted to such a node,

Algorithm 1 Get the Number of Hops

1: N_h =0, dd = L;//N_h represents the number of hops
2: **while** dd>r
3: N_h++;
4: $ohd = \int_{r_0}^{r} x \cdot \frac{2(dd-x)}{S_{dd}^{r_0}} cos^{-1}\left[\frac{dd^2+(dd-x)^2-r^2}{2dd(dd-x)}\right]dx$;
5: $dd = dd\text{-}ohd$;
6: **End while**
7: **Return**N_h

the next hop will be transmitted directly to the sink node, regardless of the transmission delay. The number of hops needed to route to sink from the source node whose distance from sink is Lm is shown in Algorithm 1.

Figure 25 shows the effect of r_0 on the number of hops. It can be found that the number of hops decreases stepwise with the increase of r_0. This reason is that the increased one hop forward distance does not reduce the number of hops when r_0 is in a certain interval. For example, when r_0 is in the range of 20~38, the number of hops at L = 300m is 5, while when r_0 = 40, the number of hops decreases to 4.

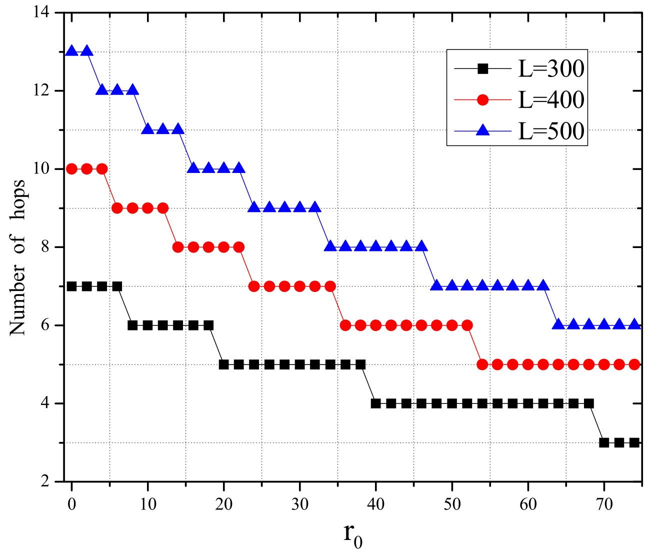

FIGURE 25. The number of hops varies with r_0.

Figure 26 shows that the number of hops needed to route to sink at different distances. It can be found that when r_0 = 40, the number of hops at L = 400m is reduced from 10 to 6, and the number of hops at L = 500m is reduced from 13 to 8, and the number is respectively reduced by 40.0% and 38.4%.

End-to-end delay is the sum of all forwarding delay on the path. After getting the number of hops and delay per hop, end-to-end delay can be obtained:

$$D_{e2e}^{L} = \sum_{i=1}^{N_h} D_i \tag{30}$$

where, N_h is the number of hops and D_i is the one-hop delay of i-th hop.

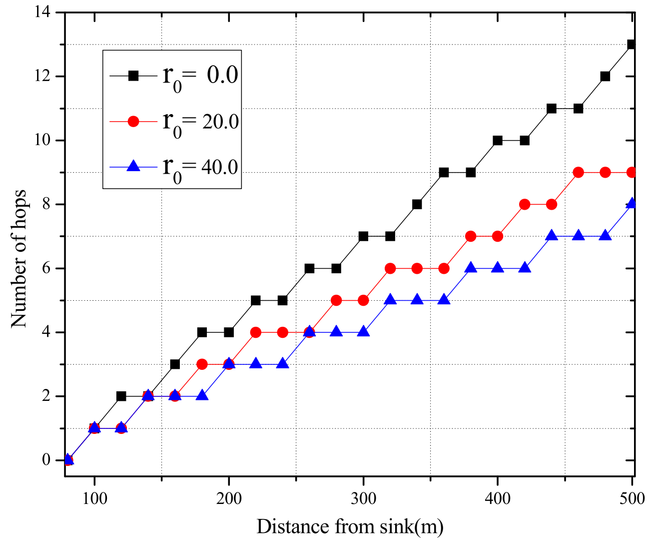

FIGURE 26. Number of hops required for source nodes to route to sink at different distance.

B. ODC-SFNS STRATEGY

1) OPTIMAL ALGORITHM OF DENSE NETWORK

Strategy 1 of this paper is to minimize one hop delay and the number of hops in dense networks, i.e. networks with $n\times(1/\tau) > 1$, by setting appropriate r_0 at different distances. In the analysis of the previous section, we have explained the effect of r_0 on the one hop delay and the number of hops. For different network conditions or different distances from sink, r_0 is different. According to the node density of the network, the number of slots per cycle and the distance from sink, the r_0 which minimizes one hop delay is obtain. The following algorithm can be used to obtain the r_0 that minimizes the one hop delay, and gain the end-to-end delay.

2) OPTIMIZING METHOD OF SPARSE NETWORK

In sparse networks, $n \times (1/\tau) < 1$, at which time, too few candidate nodes or too low duty cycle are the main factors causing delay, and increasing the number of nodes in the network is often expensive or impossible, so we consider increasing the duty cycle of nodes. Due to the characteristics of wireless sensor network data convergence to the center, the node near the sink has a large load and fast energy consumption. As shown in Figure 15, the load at L = 100m is significantly larger than the far sink region. Strategy 2 in this paper is to increase the duty cycle Ω of the far-sink region node by using the residual energy in the sparse network. Since $\Omega = {}^{1}\!/_{\tau}$, increasing Ω means decreasing τ, thus the one-hop expected delay of sparse networks will be reduced and energy utilization will be improved.

In order to facilitate calculation, we set the energy consumption of sending a packet as ω_t, receiving a data packet as ω_t and idle state as ω_l. The initial duty cycle is Ω_{hot}, and the time of a cycle is T_{hot}. Then the time length of the active

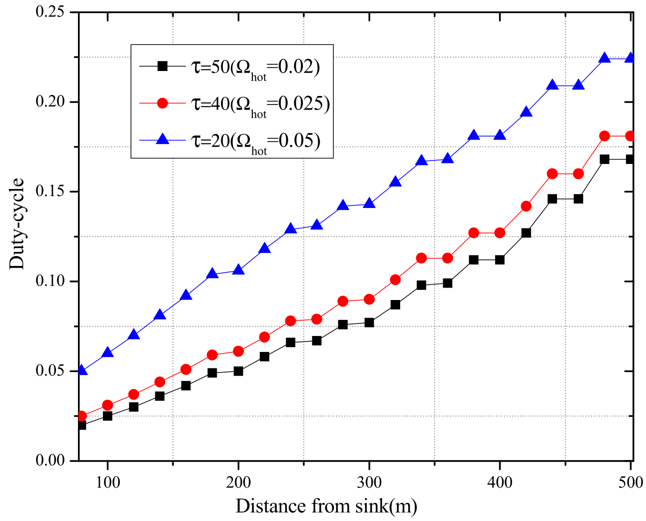

FIGURE 27. Duty cycle at different distances.

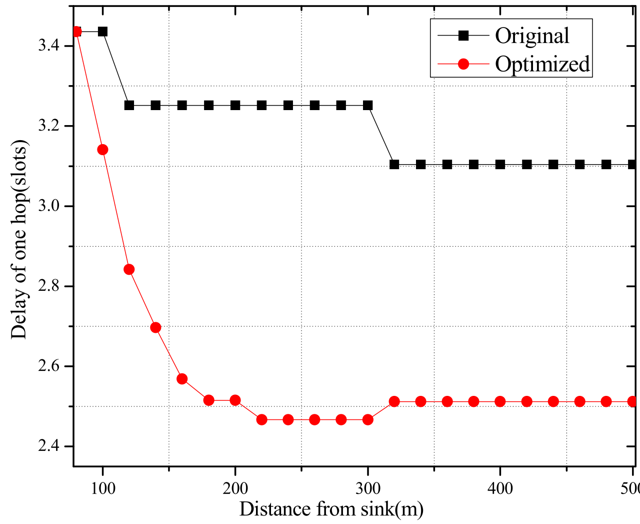

FIGURE 29. The excepted delay of one hop before and after optimization ($\tau_{hot} = 20, \rho = 0.001$).

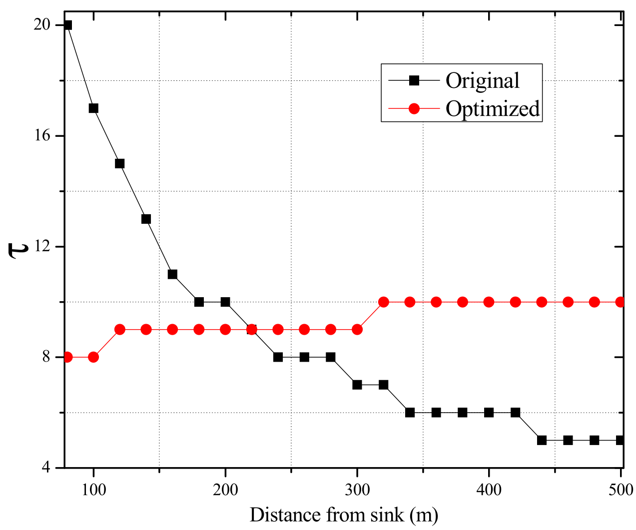

FIGURE 28. τ_e and τ_o at different distance when $\tau_{hot} = 20$.

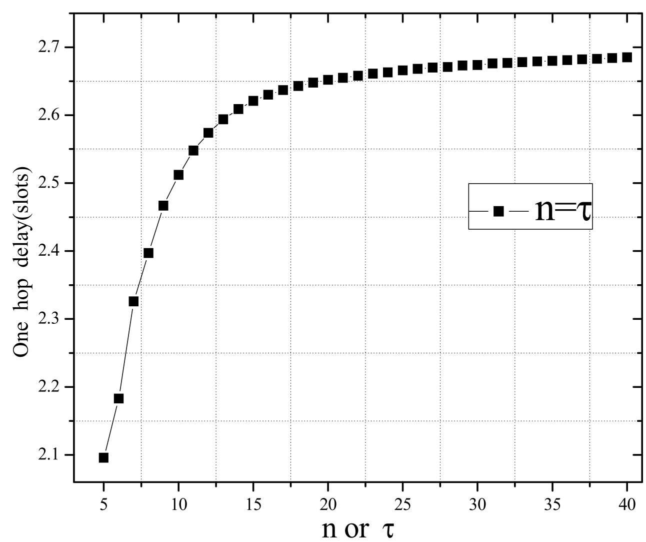

FIGURE 30. Variation of the minimum one-hop delay with the increase of τ or n.

mode is

$$T_a = \Omega_{\text{hot}} * T_{\text{hot}} \tag{31}$$

Assuming that the distance between a node and sink is Lm, the energy consumption of transmitting data is as follows:

$$E_t^L = \omega_t * \left(\mathbb{N}_R^L + 1\right) * \mu \tag{32}$$

The energy consumption of receiving data is as follows:

$$E_r^L = \omega_r * \mathbb{N}_R^L * \mu \tag{33}$$

The energy consumption of idle is:

$$E_l^L = \left[T_a - \left(\mathbb{N}_R^L + 1\right) * \mu * t_{s\_r} - \mathbb{N}_R^L * \mu * t_{s\_r}\right] * \omega_l \tag{34}$$

Then, the energy consumption of a node whose distance from sink is Lm in a cycle is as follows:

$$E_L = e_t^L + e_r^L + e_l^L \tag{35}$$

where $\mathbb{N}_R^L$ is the number of received packets, μ is the probability of packet generation, and t_{s_r} is the duration of receiving/sending a packet.

Theorem 4: If the energy consumption of a node near sink is E_{hot} in a cycle, the energy consumption of a node whose distance from sink is Lm in a cycle is E_L, and the initial duty cycle is Ω_{hot}, if the residual energy of the node is all used to increase the duty cycle, then the increased duty cycle of a node whose distance from sink is Lm is:

$$\Omega_L = \Omega_{hot} \times \frac{E_{hot}}{E_L} \tag{36}$$

Proof: If the residual energy is all used to increase the duty cycle, the energy consumption of the nodes in the network is the same in unit time, that is,

$$\frac{1}{T_{\text{hot}}} * E_{hot} = \frac{1}{T_L} * E_L \tag{37}$$

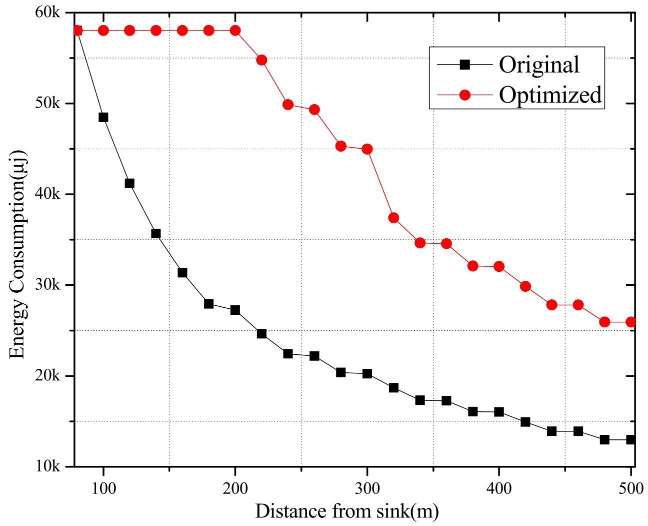

FIGURE 31. Energy consumption of nodes per unit time.

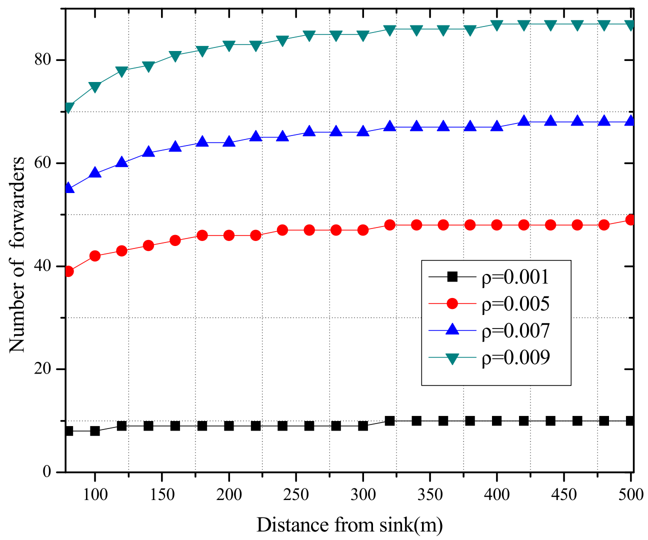

FIGURE 32. Number of candidate nodes at different distance.

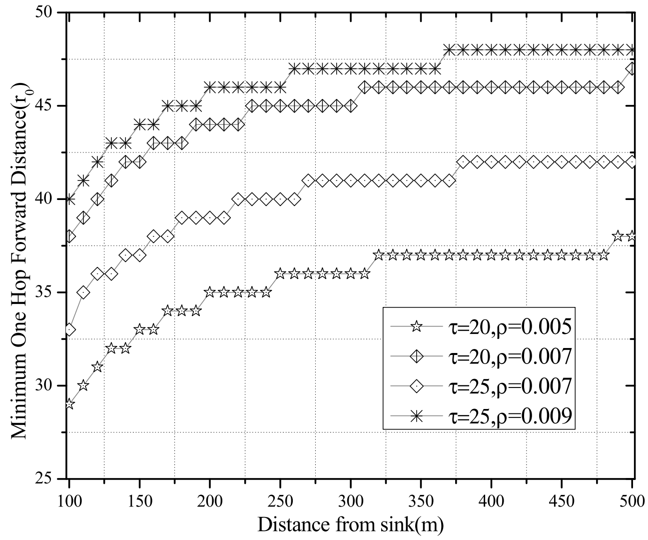

FIGURE 33. r_0 at different distance of different networks.

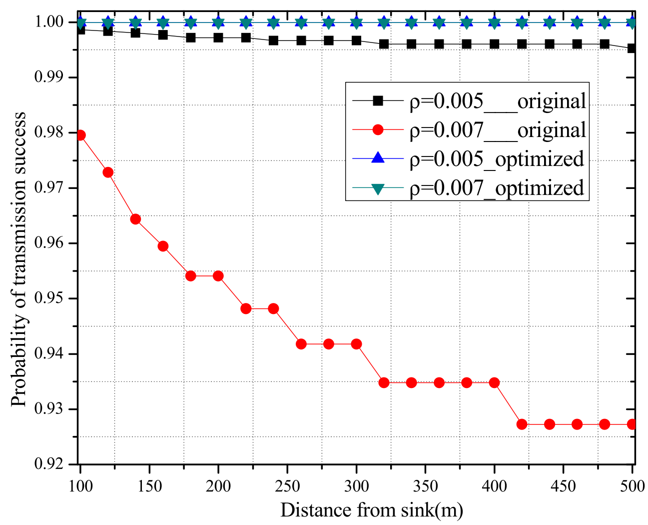

FIGURE 34. Probability of successful transmission in a cycle when τ =20.

where, T_{hot} is the time length of the node near sink, which is equal to the initial time length of all the nodes in the network. T_L is the time length of the node whose distance from sink is Lm after increasing duty cycle.

Then,

$$T_L = \frac{E_L}{E_{hot}} \times T_{\text{hot}} \tag{38}$$

So, the adjusted duty cycle is:

$$\Omega_L = \frac{T_a}{T_L} \tag{39}$$

$$= \frac{T_a}{T_L} \times \frac{E_{hot}}{E_L}$$

$$= \Omega_{hot} \times \frac{E_{hot}}{E_L} \tag{40}$$

The theorem is proved. ■

Because of the time-slot model adopted in this paper, the duty cycle is expressed by the number of time slots per cycle. For convenience of analysis, the value of τ varies from 10 to dozens.

From formula (36), we can get the adjusted duty cycle everywhere in the network. In Figure 27, when $\Omega_{hot} = 0.02$, the duty cycle increases by 3.8 times at $L = 300$m.

We always expect to adjust τ to $\tau = n$ everywhere in the network. However, due to the difference of residual energy, there may be regions where the energy remains after $\tau = n$, and some regions where the delay is reduced after adjustment, but n is still less than τ. The number of slots per cycle obtained by increasing duty cycle with all residual energy is counted as τ_e, and the number of slots per cycle that minimize the delay of one jump is counted as τ_o. The number of time slots

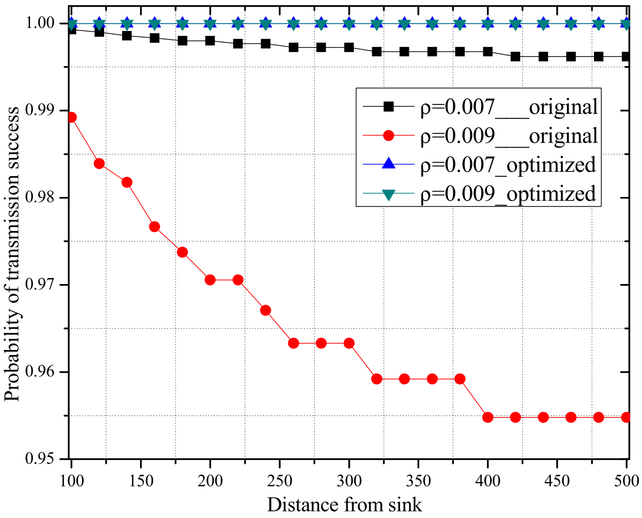

FIGURE 35. Probability of successful transmission in a cycle when τ =25.

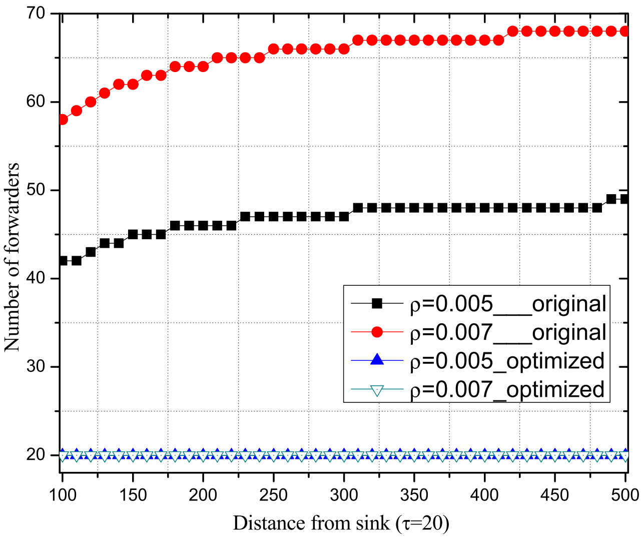

FIGURE 36. Comparison of the number of candidate nodes.

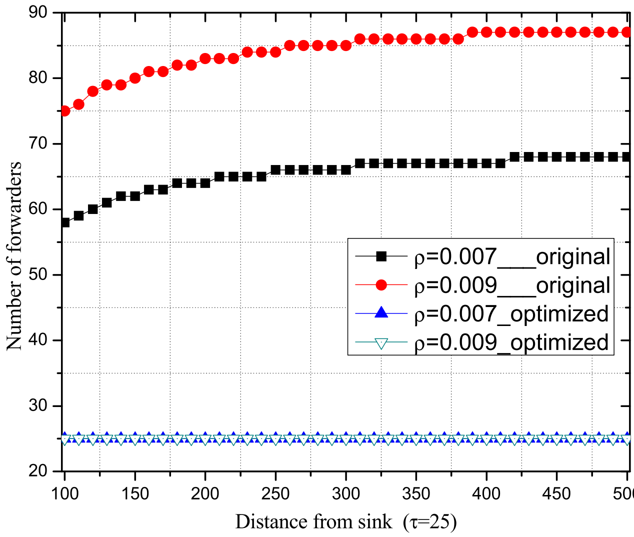

FIGURE 37. Comparison of the number of candidate nodes.

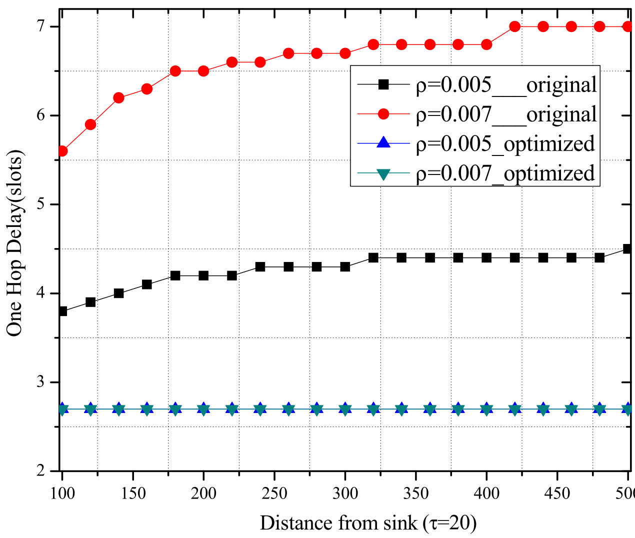

FIGURE 38. The one-hop delay before and after optimization.

actually used needs to consider the size of τ_e and τ_o. If $\tau_e < \tau_o$, take $\tau = \tau_o$, otherwise, take $\tau = \tau_e$,as shown in Algorithm 3:

Figure 28 shows τ_e and τ_o everywhere in the network when ρ= 0.002. The actually used τ is the larger of the two. In the region where the residual energy is relatively small, as shown in Figure 28, where $L \leq 220$, $\tau_e > \tau_o$, take $\tau = \tau_o$. The region with sufficient residual energy, where $L \geq 220$, take $\tau = \tau_e$.

Figure 29 shows the excepted delay of one hop before and after optimization using strategy 2. In the original state, the farther away from sink, the smaller the delay of one hop is, as shown in Figure 29. Because $n < \tau$ is the main cause of delay in sparse networks, the farther the distance is, the more the number of candidate nodes, the closer the value of n is to τ, so the delay of one hop delay in the distance is smaller. After the optimization of strategy 2, the expected delay of one hop is reduced. For example, at L = 250m, the expected delay of one hop is shortened by 24%.

In fact, even if $n = \tau$ exists everywhere in the network, the minimum delay increases with the increase of τ or n, as shown in Figure 30. This is the reason why the delay in the region of $L > 300$ in Figure 29 is larger than the delay in the region of $220 < L < 300$. At the same time, it provides a basis for the proposal of comprehensive strategy.

Figure 31 shows the energy consumption per unit time before and after optimization using Strategy 2. In the original state, as the distance increases, the amount of data carried by nodes is less and less, and the energy consumption of nodes is less and less. After using strategy 2 to increase the duty cycle, the energy utilization rate is improved. In Figure 31, in the region of $L \leq 220$, the energy consumption is the same as the hot zone. Compared with Figure 28, we find that the region of

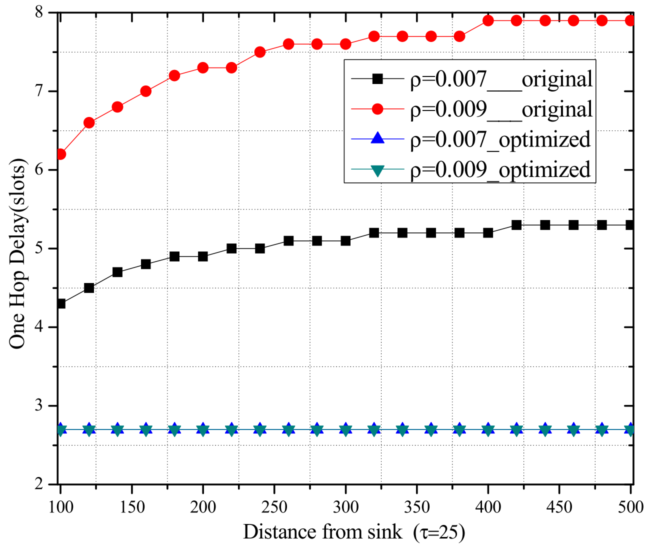

FIGURE 39. The delay of one hop before and after optimization.

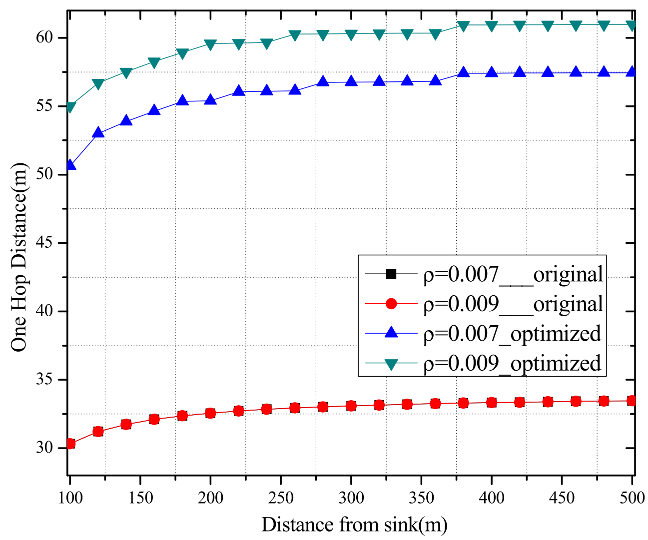

FIGURE 41. One hop forward distance (τ =25).

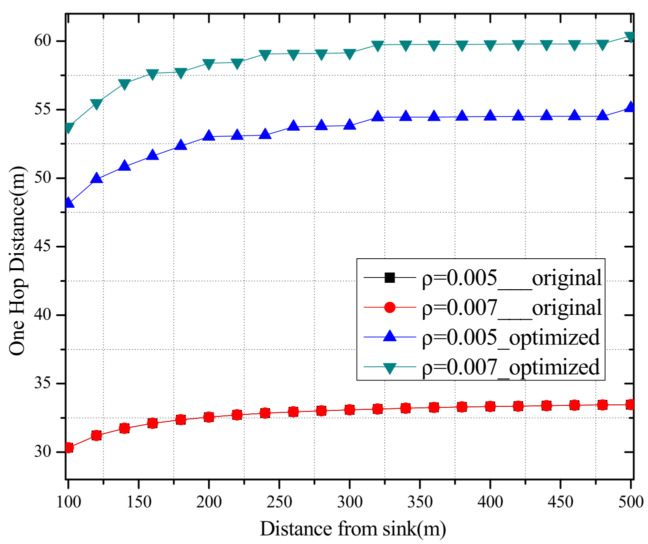

FIGURE 40. One hop forward distance (τ =20).

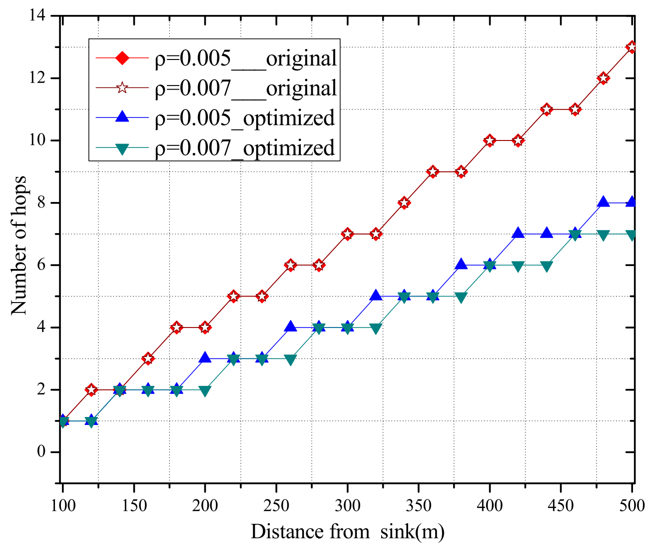

FIGURE 42. The number of hops (τ =20).

$L \leq 220$ is the region of $\tau_o \leq \tau_e$, where the residual energy is all used to increase the duty cycle. The region of $L > 220$ is the region of $\tau_o > \tau_e$, in which the residual energy of nodes is not fully utilized. This situation also provides a basis for the proposal of comprehensive strategy.

(3) Comprehensive Strategy

In dense networks, after setting r_0 which makes $n = \tau$, although the network has achieved the minimum delay of one hop everywhere, the residual energy of the networks has not been effectively utilized. If we continue to increase r_0, reduce the number of candidate nodes n, and use the method of strategy 2 to increase the duty cycle with residual energy, that is to say, to reduce τ.This first results in a smaller delay of one hop, as shown in Figure 30. Secondly, continuing to increase r_0 will further increase the one hop forward distance, which will result in less hops and further shorten the end-to-end delay. Increasing r_0 also reduces network load, which reduces energy consumption and makes nodes have more residual energy to utilize. For sparse networks, except for some region mentioned in the previous section, the residual energy is not fully used, and increasing r_0 also has the same situation as dense networks.

Therefore, considering comprehensively, we adopt the methods of strategy 1 and strategy 2 in the network at the same time. Setting suitable r_0 at different distance from sink and using residual energy to increase duty cycle may result in a smaller delay and higher energy utilization. This Comprehensive Strategy will be applicable to networks with arbitrary ratios of $^{n}/_{\tau}$.

Algorithms of Comprehensive Strategy is:

VI. ANALYSIS OF EXPERIMENTA RESULTS

In this chapter, we will analyze the performance of Strategy 1, Strategy 2 and Comprehensive Strategy, compare

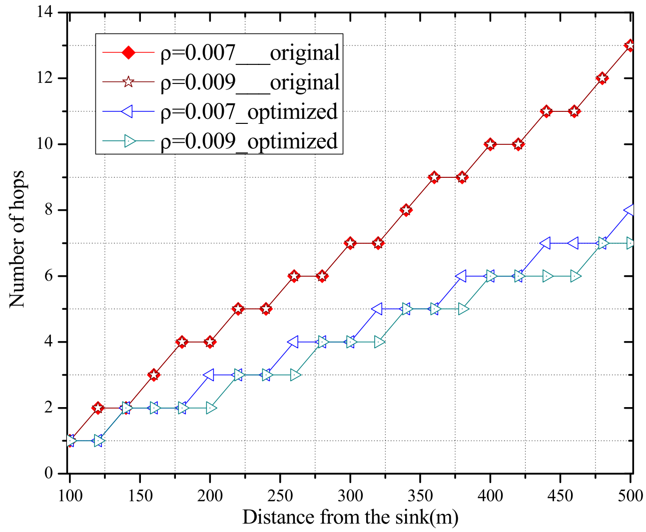

FIGURE 43. The number of hops (τ =25).

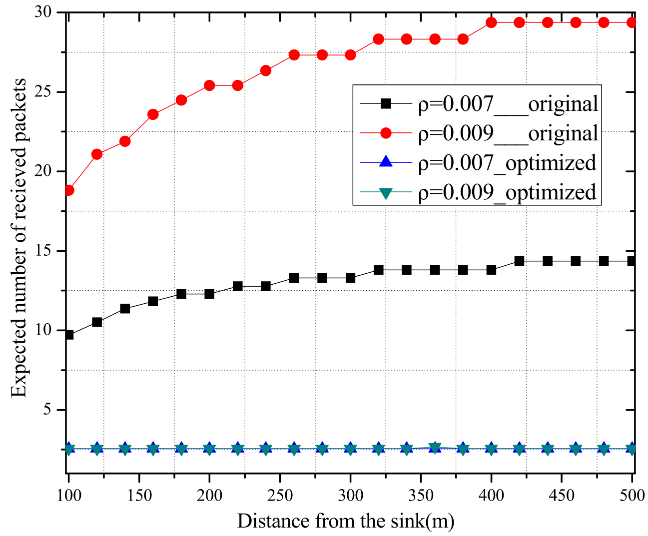

FIGURE 45. Expected number of packets received per transmission (τ =25).

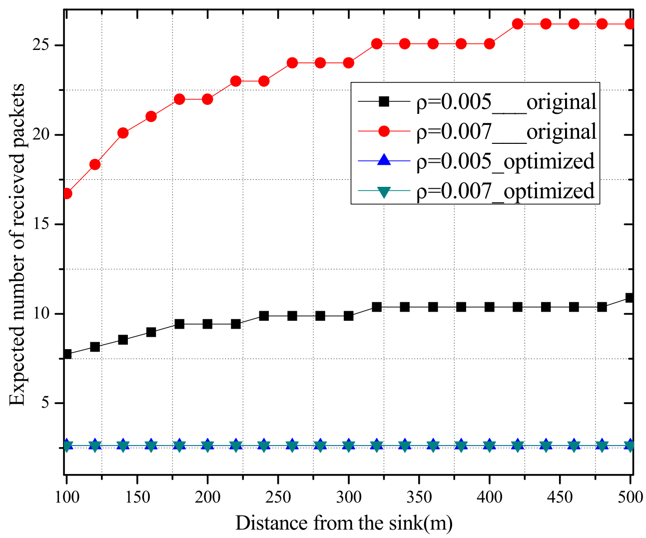

FIGURE 44. Expected number of packets received per transmission (τ =20).

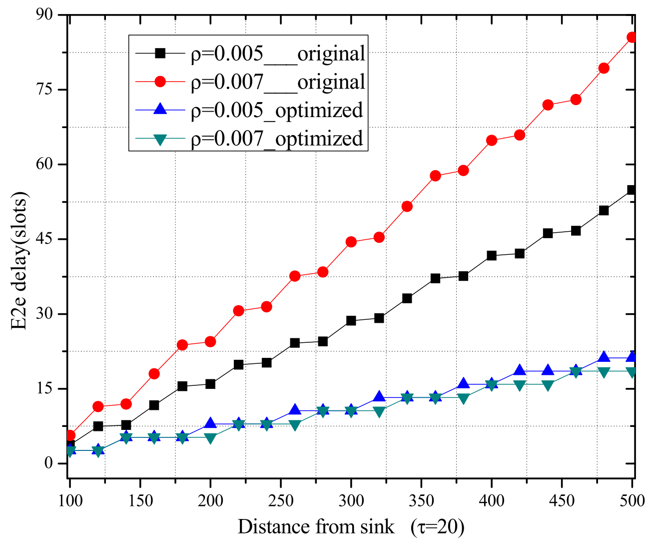

FIGURE 46. Comparison of end-to-end delay before and after optimization.

the parameters before and after the adoption of Strategy 1 and Strategy 2, and compare how much the comprehensive strategy optimizes the network based on strategy 1 or strategy 2.

A. EXPERIMENT SETUP

Experimental scenario is as follows:

The two strategies discussed in this paper are for dense and sparse networks. Dense and sparse are relative. The network with $n \times (1/\tau) > 1$ is called dense network, and the network with $n \times (1/\tau) < 1$ is called sparse network. Figure 32 shows the number of candidate nodes n in the network with different node densities. In the network with node density $\rho = 0.001$, the number of candidate nodes ranges from 8 to 10 from near to far. The number of candidate nodes varies from 42 to 48 in a network with $\rho = 0.005$. For the network with $\rho = 0.007$ and the network with $\rho = 0.009$, the numbers of candidate nodes range from 55 to 68 and 71 to 87, respectively.

If τ is not allowed to be greater than 20 in practical application, $n \times (1/\tau)$ range from 2.1 to 2.4 and 2.75 to 3.4 for network with $\rho = 0.005$ and network with $\rho = 0.007$. If τ is not allowed to be greater than 25, $n \times (1/\tau)$ range from 2.2 to 2.72 and 2.84 to 3.48 for the network with $\rho = 0.007$ and the network with $\rho = 0.009$. They are dense networks.

If the density of the network is ρ= 0.001 and the requirement is that τ should not be greater than 40 or 50, then the values of $n \times (1/\tau)$ are 0.2-0.25 or 0.16-0.2, respectively. They are sparse networks.

B. PERFORMANCE ANALASIS OF STRATEGY 1

For dense networks, we use Algorithm 2 to get r_0 for different networks, which is shown in Figure 33.

As shown in Figure 34, in the same network, the farther the sender distance from the sink, the larger the area of

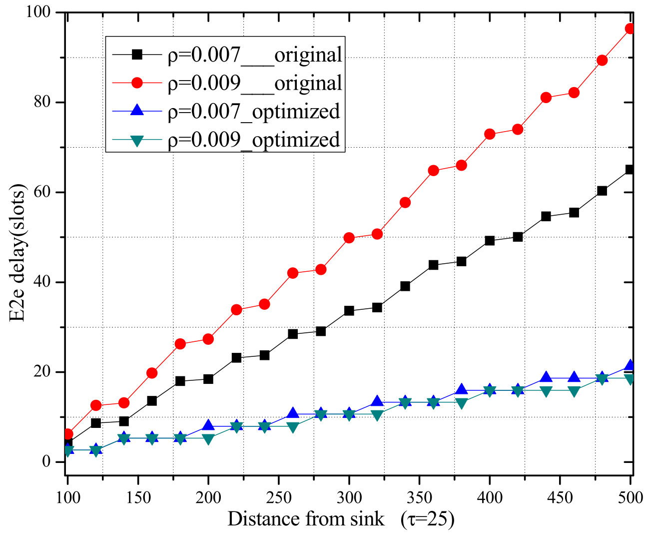

FIGURE 47. Comparison of end-to-end delay before and after optimization.

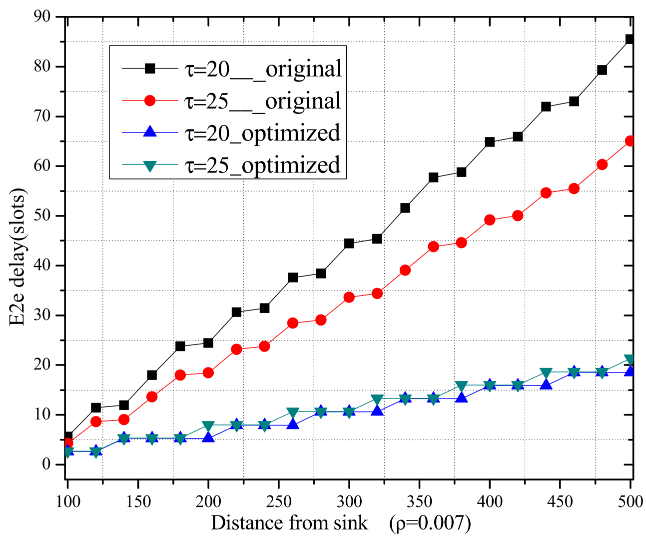

FIGURE 48. Comparison of optimized effects of different duty cycle with the same density.

the candidate node region is, and the more the number of candidate nodes is, so the greater the value of r_0 that needs to be set. Similarly, for a network with the same number of time slots per cycle, the network with the larger density needs to set a larger r_0.

As mentioned in 4.1 of this paper, this model assumes that the transmission is successful in one cycle. Therefore, the probability of successful transmission in one cycle should be as large as possible. Figure 34 and Figure 35 show the probability of successful transmission in different networks before and after optimization using strategy 1. As can be seen from Figure 34 and Figure 35, the probability of successful transmission in one cycle of the original network is higher than 92%, and the probability of successful transmission of the optimized network using strategy 1 is almost 100%.

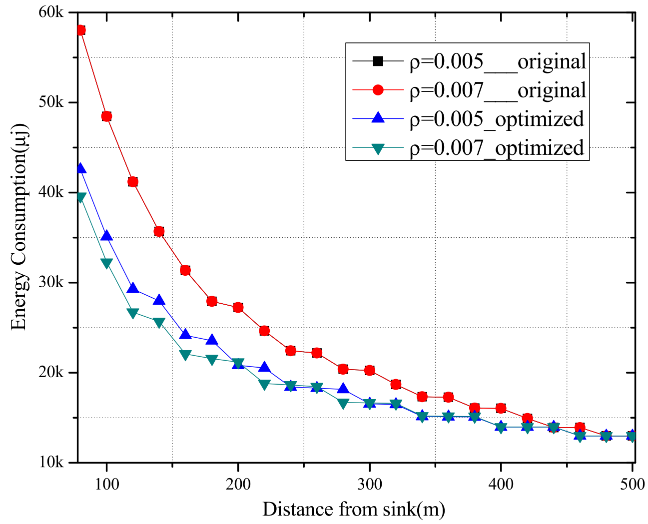

FIGURE 49. Energy consumption of sensor nodes in unit time when τ =20.

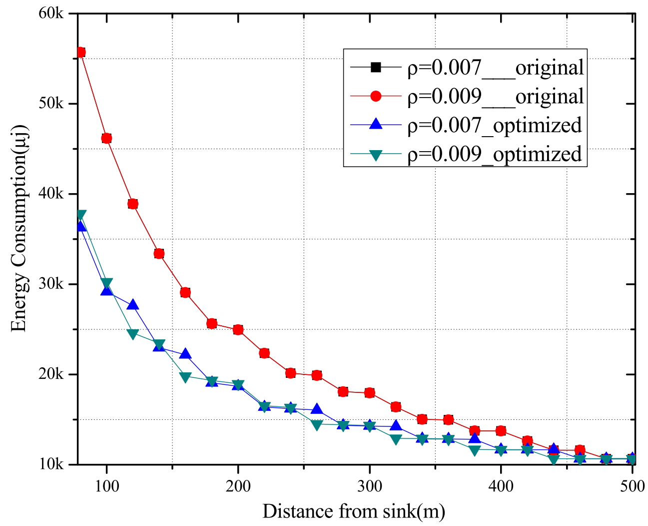

FIGURE 50. Energy consumption of sensor nodes in unit time when τ =25.

Algorithm 2 Get r_0 and e2e Delay

```
D_e2e =0.0, dd = L; buff = 0.0;
while dd > r
  Delay= ∞
   For y from 0 to r Do
     n= S^y_dd * ρ
     If D^τ_n < Delay
       Delay= t^τ_n, buff = y
    End if
   End for
  r_0 = buff;
dd = dd-ohd, D_e2e = D_e2e+Delay
End while
Return D_e2e
```

After the minimum one hop forward distance r_0 is set, the area of candidate nodes region is reduced and the number

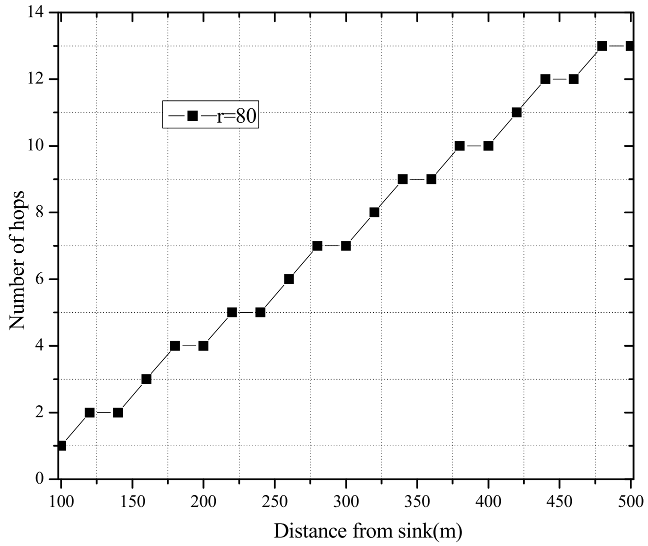

FIGURE 51. The number of hops when $r_0 = 0$.

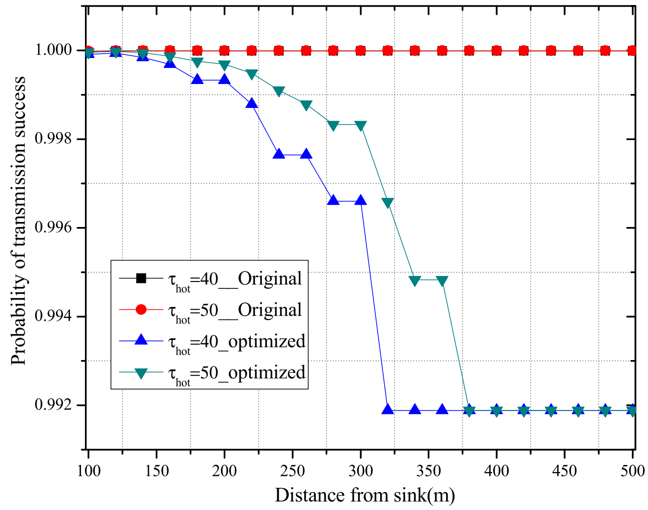

FIGURE 53. The probability of successful transmission at different distance from sink.

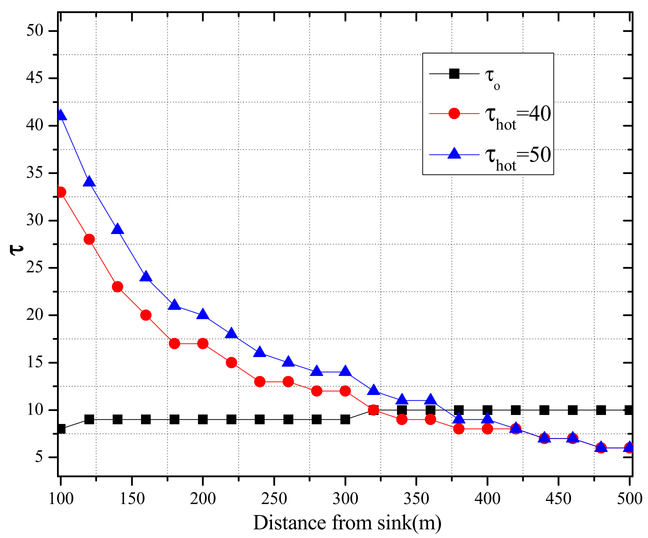

FIGURE 52. τ_e & τ_o of different networks.

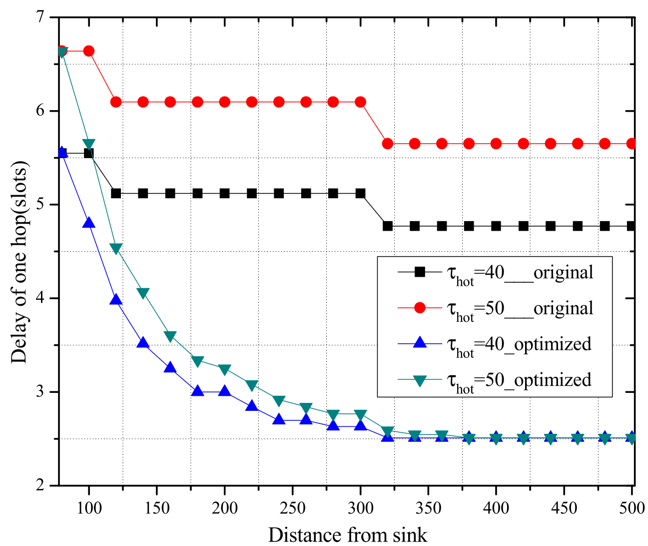

FIGURE 54. One-hop delay at different distance from sink.

of candidate nodes is reduced accordingly. Figure 36 and Figure 37 show the changes in the number of candidate nodes before and after setting r_0. In Figure 37, the number of candidate nodes at 300m in the network with $\rho = 0.009$ is reduced by 70.5% after optimization.

After r_0 is set everywhere in the network, the delay of one hop is optimized. Figure 38 and Figure 39 show the delay of one hop before and after optimization. In Figure 39, in the network with $\rho = 0.009$, the delay of one hop at $L = 300$m is only 38.9% after optimization.

When r_0 is set, one hop forward distance is increased. Figure 40 and Figure 41 show the one hop forward distance everywhere in the network corresponding to r_0 in Figure 33. In Figure 41, in the network with $\rho = 0.009$, the one hop forward distance at 300m increases by 1.8 times after optimization.

The number of hops in the original state depends only on the distance between source node and sink, as shown in Figure 42 and Figure 43, the number of hops at different distance in the original state is the same. After setting r_0, the forward distance of one hop is increased, which reduces the number of hops. And the network with the higher density, the larger the r_0, the larger the number of hops, and the smaller the number of hops will be. In Figure 42 and Figure 43, after optimization, the number of hops at 500m decreases by one hop in the dense network than in the less dense network. As shown in Figure 42, in the network with $\tau = 20$ and $\rho = 0.007$, the number of hops from the source node whose distance from sink is 500m to sink is reduced from 13 to 7, which is reduced by 46.2%.

Reducing the number of candidate nodes will reduce the probability of collision. The expected number of packets

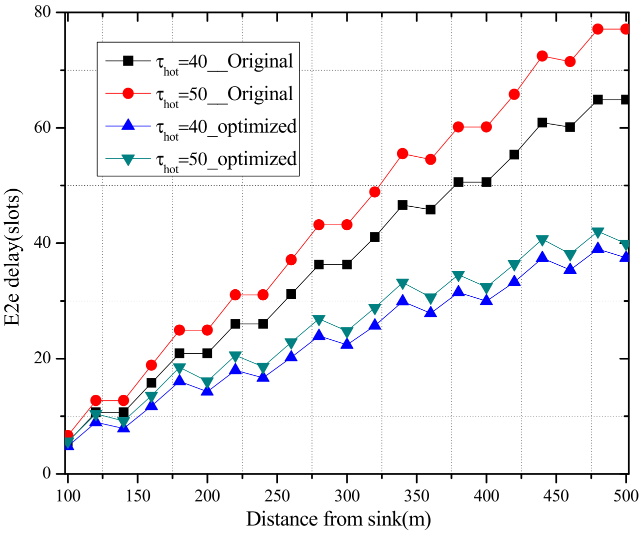

FIGURE 55. End-to-end delay before and after strategy 2 optimization.

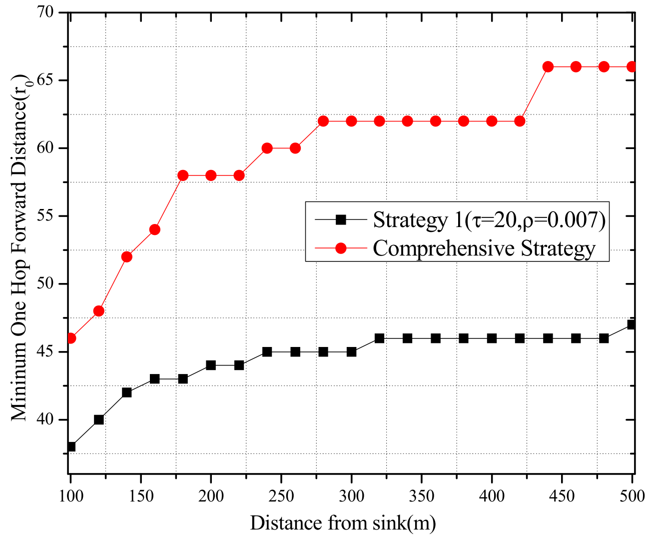

FIGURE 57. Comparison of r_0 in dense network.

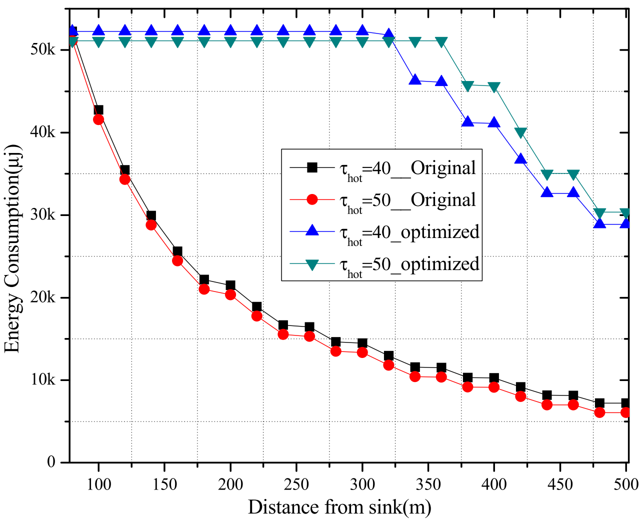

FIGURE 56. Energy consumption per unit time.

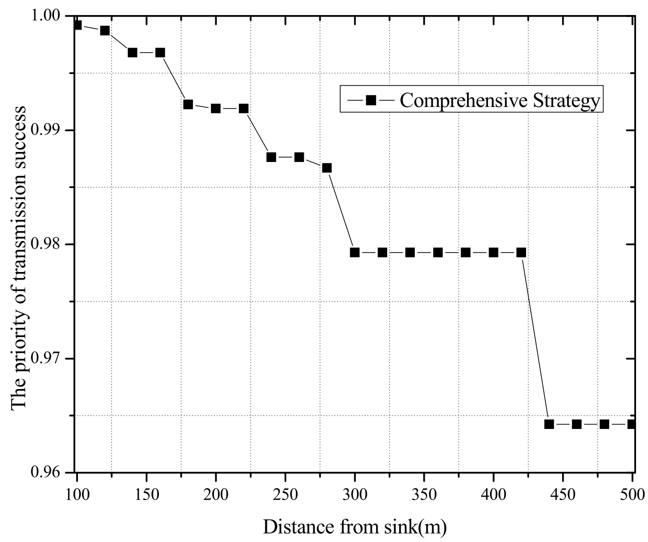

FIGURE 58. The probability of successful transmission of comprehensive strategy.

received per transmission reflects the collision situation. Figure 44 and Figure 45 show that setting r_0 can effectively reduce the conflict. In the network of τ =25 and ρ= 0.009, the conflict decreases by 91.3% at $L = 500$m.

With the decrease of one-hop delay and number of hops, the end-to-end delay of dense networks can be effectively reduced. In Figure 46, in the network with the number of slots per cycle $\tau = 20$ and the node density $\rho = 0.005$, the end-to-end delay at $L = 100$m is reduced by approximately 30%, the end-to-end delay is reduced by approximately 62.9% at $L = 300$m, and approximately 61.3% at $L = 500$m. In Figure 47, the end-to-end delay is higher due to the higher node density, so the optimization effect of strategy 1 is more significant. When $\rho = 0.009$, the delay is shortened by 78.68% at $L = 300$m.

Figure 48 shows the comparison of end-to-end delay in different networks with the same node density and different initial number of slots per cycle using strategy 1 before and after optimization. We find that the larger the initial value of τ, the smaller the delay. This is because the number of candidate nodes in dense network is larger than the number of slots is the main factor causing the delay, so the larger the τ, the smaller the delay. Moreover, it is found that the end-to-end delay of different ρ but same τ varies little after optimization.

After setting r_0, the load of the network is reduced, and the energy consumption of the network is reduced accordingly, as shown in Figure 49 and Figure 50.

C. PERFORMANCE ANALYSIS OF STRATEGY 2

When $^{\eta}/_{\tau} < 1$, the delay caused by waiting for the wakeup of the candidate node becomes the main factor of the

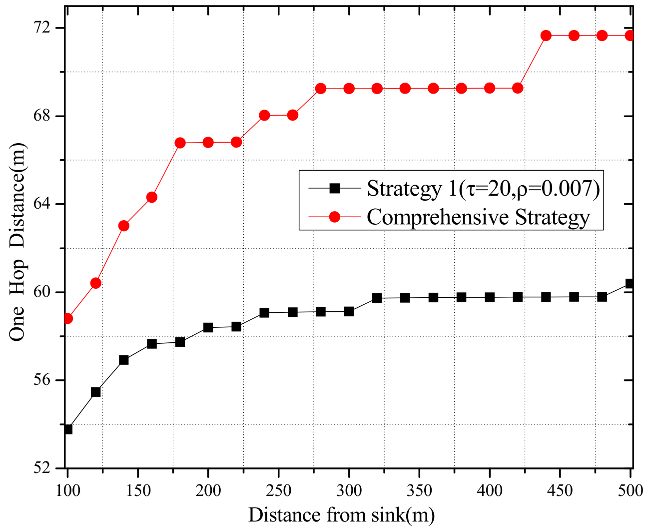

FIGURE 59. Comparison of one hop forward distance after strategy 1 and comprehensive strategy optimization.

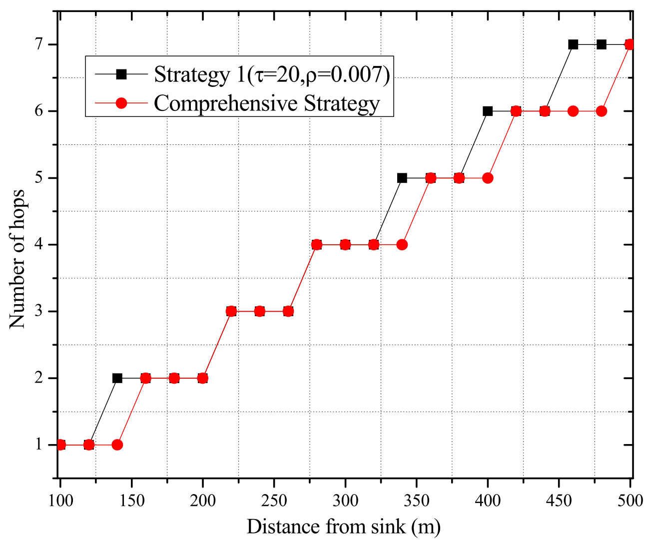

FIGURE 60. Comparison of the number of hops required for strategy 1 and comprehensive strategy.

one-hop delay. Using the residual energy to increase the duty cycle can effectively reduce the delay.

First, because the minimum one-hop forward distance $r_0 = 0$ in Strategy 2, the number of hops of different network depends only on the transmission radius and distance from sink, so the network with the same transmission radius, different node density ρ, and different number of slots per cycle, the number of hops at the same distance is the same. The number of hops of the networks with transmission radius $r = 80$ is shown in Figure 51.

Using algorithm 3, the minimum number of time slots τ_e obtained by using residual energy is shown in Figure 52. Due to the node density of different networks in Experiment 2 is $\rho = 0.001$, the number of nodes at the same distance in different networks is the same, so the τ_o of different networks

Algorithm 3 Get τ

```
τ_hot = 1/Ω_hot; buff= τ_hot;
get Ω_L from formula (36), τ_e = 1/Ω_L;
Delay = ∞
  For y from τ_hot to 1 Do
    get D_y^n formula (7)
    If Delay > D_y^n
      Delay = D_y^n, buff = y;
    End If
  End For//Delay is the minimum delay when End For
τ_o = buff;
If τ_e < τ_o
  τ = τ_o;
else
  τ = τ_e;
End If
```

is the same. Because of the farther away from sink, the more residual energy of the node, the smaller τ_e can be obtained. In Figure 52, in the network of $\tau_{hot} = 40$, in the region of $L > 320$, $\tau_e \leq \tau_o$.

Before and after the optimization of strategy 2, the probability of successful transmission is greater than 92% everywhere in the network, as shown in Figure 53. So, the strategy 2 presented in this paper can be used.

After optimization, τ takes the larger of τ_e and τ_o in Figure 52, then we obtain one-hop delay before and after optimization by equation (24), as shown in Figure 54. In the network with $\tau_{hot} = 50$, at $L = 300$m, the one-hop delay is reduced by 54.7%.

Reducing the delay of each hop in the packet transmission path can significantly reduce the end-to-end delay. Figure 55 shows the end-to-end delay before and after optimization using Strategy 2. At $L = 300$m, the network with $\tau_{hot} = 40$ has a 42.8% end-to-end delay.

After optimizing the network using Strategy 2, the residual energy in the network is effectively utilized. Especially in the region of $\tau_e \geq \tau_o$, the residual energy will all be used to increase the duty cycle. The energy consumption in these regions is the same as that in the hot zone. In Figure 56, the energy utilization rate in the region of $L < 300$m is 100%.

D. PERFORMANCE COMPARISION BETWEEN COMPREHENSION STRATEGY AND STRATEGY 1 & STRATEGY 2

This section draws a conclusion from the experimental data that the comprehensive strategy has better performance than strategy 1 for dense networks or strategy 2 for sparse networks.

1) Contrast with Strategy 1

Firstly, in the dense network with $\tau = 20$ and $\rho = 0.007$, the comparison of strategy 1 and comprehensive strategy is made. The r_0 obtained by using Algorithm 2 and

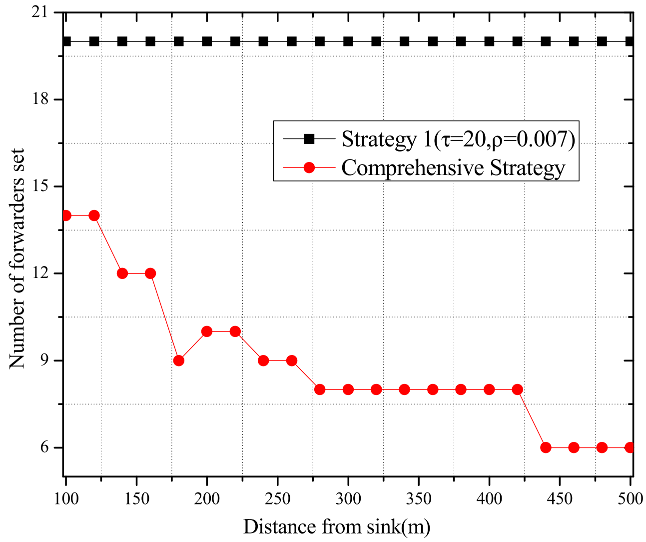

FIGURE 61. Comparison of the number of candidate nodes after strategy 1 and comprehensive strategy optimization.

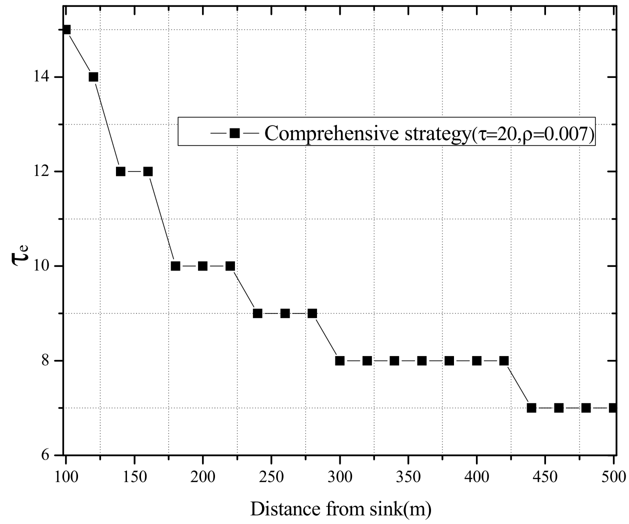

FIGURE 62. The minimum number of slots that can be obtained.

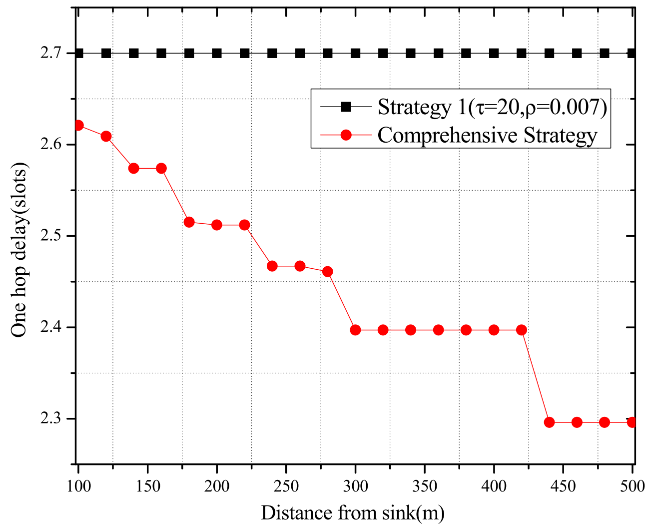

FIGURE 63. Comparison of delay of one hop after strategy 1 and comprehensive strategy optimization.

Algorithm 4 is shown in Figure 57. Obviously, the r_0 obtained by using the comprehensive strategy is bigger.

Algorithm 4 Comeprehensive Strategy

$\mathrm{D_{e2e}} = 0.0$, $\mathrm{dd} = \mathrm{L}$, $\mathrm{buff} = 0.0$, $\mathrm{N_h} = 0$;
while dd $> r$
  Delay$= \infty$
    For y from 0 to r **Do**
      $n = S_{dd}^{r_0} * \rho$, $\tau_o = n$;
        get one hop distance from formula 28;
        get $\mathbb{N}_R^L$ from formula 29;
        get Ω_L from formula 36, $\tau_e = 1\big/\Omega_L$;
      If $\tau_e < \tau_o$
          $\tau = \tau_o$;
        else
          $\tau = \tau_e$;
        If $\mathrm{D_n^\tau} <$ Delay
          Delay$= \mathrm{D_n^\tau}$,buff $=$ y;
      End if
  End for
$r_0 =$ buff, dd $=$ dd-ohd,$\mathrm{D_{e2e}} = \mathrm{D_{e2e}}$+Delay, $\mathrm{N_h} + +$;
End while
Return$\mathrm{D_{e2e}}$

Figure 34 has illustrated that the probability of successful transmission of a cycle is greater than 92% before and after using strategy 1 in the network with $\tau = 20$ and $\rho = 0.007$. Figure 58 shows that the probability of successful transmission in the network is more than 96% after using the comprehensive strategy.

Because the minimum forward distance r_0 of the comprehensive strategy is larger than that of the strategy 1, the forward distance *ohd* of the comprehensive strategy is larger than that of the strategy 1, as shown in Figure 59. At the distance $L = 300$m, the forward distance of one hop obtained by the comprehensive strategy is 16.9% larger than that obtained by strategy 2. This may further reduce the number of hops. As shown in Figure 60, at L =140m, 340m, 460m, the number of hops required for comprehensive strategy optimization is one less than that of Strategy 1.

In the same distance from the sink, the larger the r_0, the fewer the candidate nodes. So at the same distance, after using the comprehensive strategy to optimize the network, the sender has fewer candidate nodes, as shown in Figure 61.

Different from Strategy 1, the comprehensive strategy adopts the method of Strategy 2, which uses the residual energy to increase the duty cycle of the node. Figure 62 shows the τ_e obtained using the comprehensive strategy.

For the number of candidate nodes n in Figure 61 and τ_e in Figure 62, the number of slots per cycle that

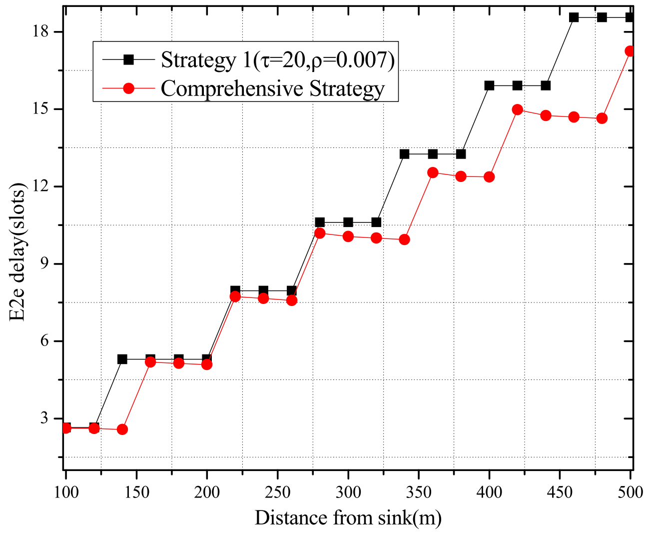

FIGURE 64. Comparison of end-to-end delay optimized by Strategy 1 and Comprehensive Strategy.

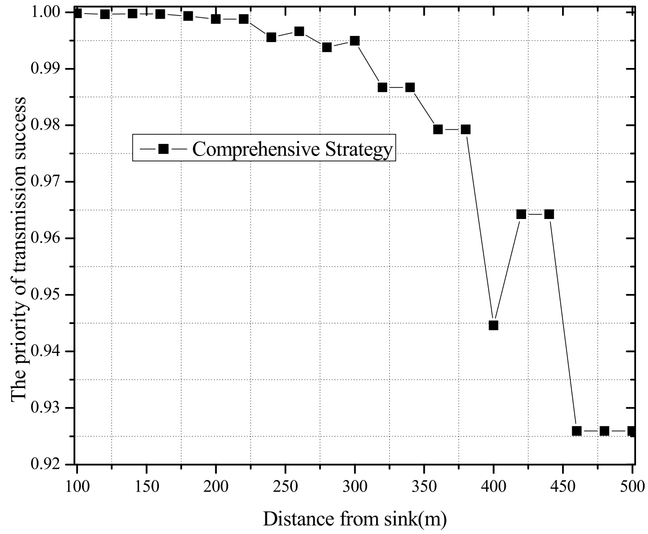

FIGURE 66. Probability of successful transmission in a cycle.

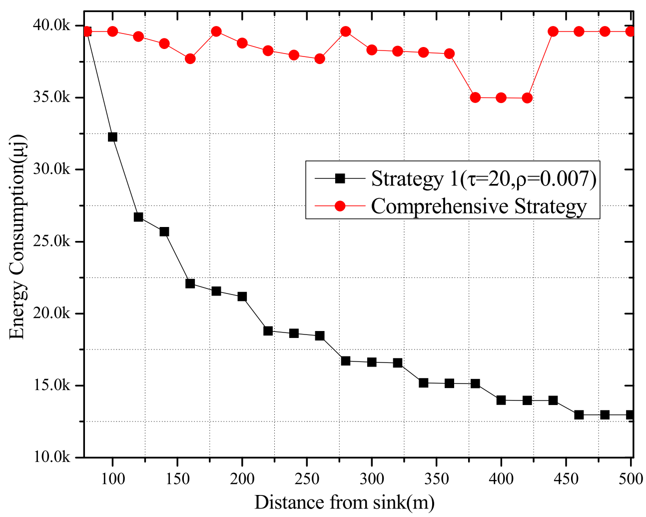

FIGURE 65. Comparison of energy consumption at different distance.

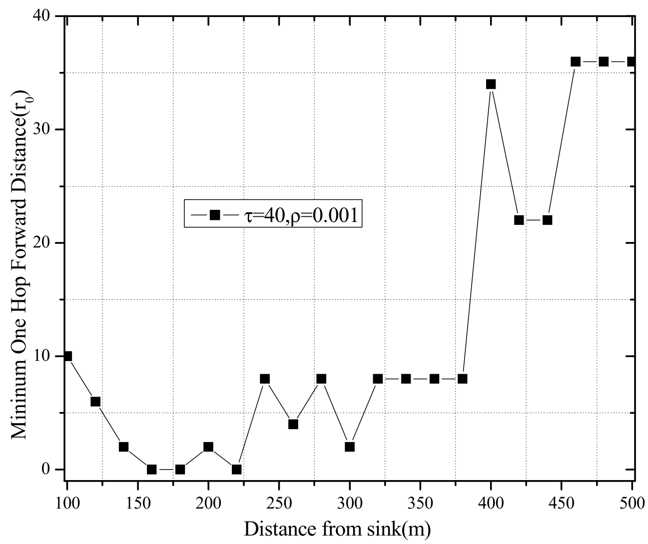

FIGURE 67. r_0 obtained by using comprehensive strategy.

minimizes the delay of one hop is selected by formula (7) to obtain the minimum delay of one hop after optimization of the comprehensive strategy. As shown in Figure 63, at $L = 500$m, the one-hop delay is reduced by 14.8% compared with strategy 1.

The end-to-end delay obtained by the comprehensive strategy will be further optimized than that obtained by strategy 1, because the comprehensive strategy achieves a smaller one hop delay and less hops than that obtained by strategy 1. As shown in Figure 64, at $L = 460$m, the end-to-end delay is further optimized by 20.9% than strategy 1, which is 79.96% better than the original situation.

And because the comprehensive strategy adopts the strategy 2 method, which use residual energy to increase duty cycle of nodes. In this way, the delay of one hop is reduced and the residual energy of the network is better utilized. That is to say, energy utilization ratio is increased. As shown in Figure 65, the energy consumption in the far sink region is much closer to that in the hot zone, which significantly better than Strategy 1.

1) Contrast with Strategy 2

Next, we compare the optimization effects of strategy 2 and comprehensive strategy in sparse networks with $\tau = 40$ and $\rho = 0.001$.

Figure 66 shows the probability of successful transmission of nodes at different distance in a cycle when using the comprehensive strategy to optimize the network. It can be found that the probability of successful transmission is greater than 92%.

r_0 is not set in strategy 2, that is $r_0 = 0$. However,the comprehensive strategy adopts the method of strategy 1,

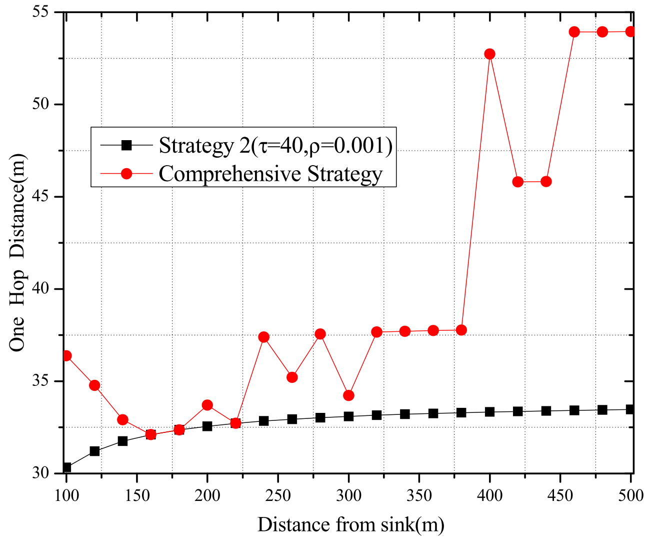

FIGURE 68. Comparison of one hop forward distance after strategy 2 and comprehensive strategy optimization.

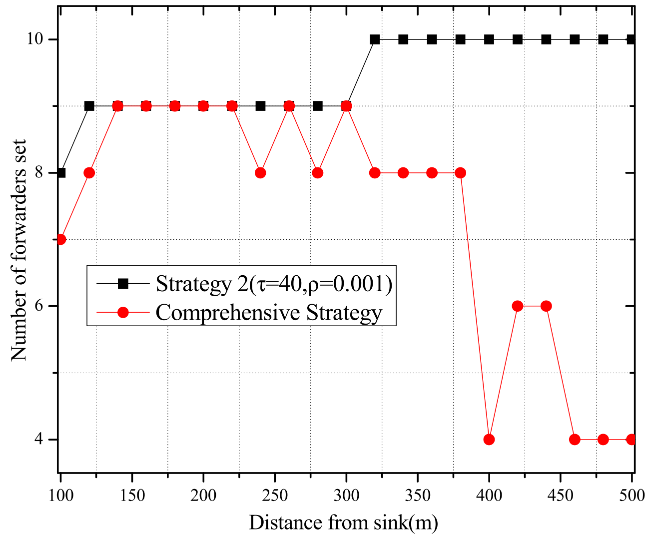

FIGURE 70. Comparison of the number of candidate nodes after strategy 2 and comprehensive strategy optimization.

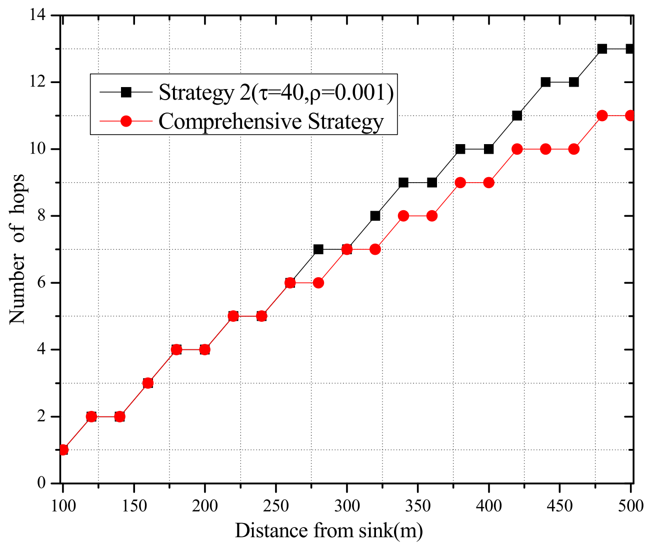

FIGURE 69. Comparison of the number of hops required for strategy 2 and comprehensive strategy.

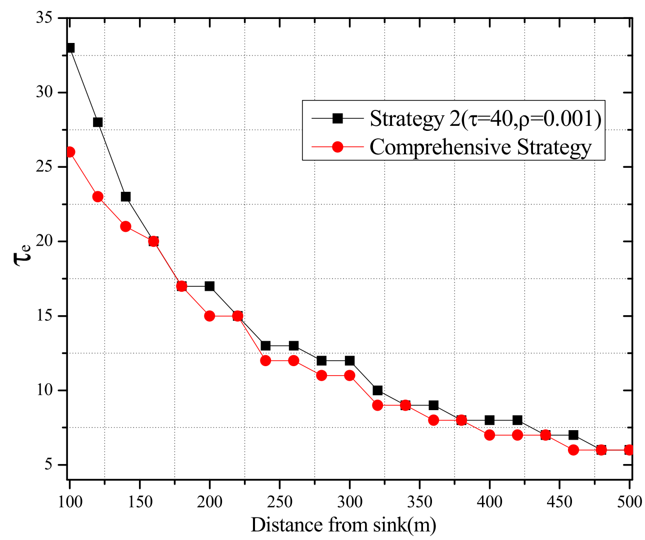

FIGURE 71. The minimum number of slots that can be obtained.

r_0 of not less than 0 is set at different distance of the network, as shown in Figure 67.

This will increase one hop forward distance where r_0 is not equal to 0. As shown in Figure 68, one hop forward distance at different distance in the network is larger when r_0 is set by the comprehensive strategy, which may reduce the number of hops needed to route packet from the source node to sink. As shown in Figure 69, in the region of $L > 260$m, the number of hops obtained by the integrated strategy optimization is less than that of strategy 2.

At the same time, after using the comprehensive strategy, the number of candidate nodes will decrease where $r_0 \neq 0$, as shown in Figure 70. Especially in regions with larger r_0, the number of candidate nodes is reduced more, such as at $L = 500$m, from 10 to 4.

The reduction in the number of candidate nodes reduces the collision and thus reduces the load, which will reduce the energy consumption of the node, so that the node has more residual energy to increase duty cycle, resulting in a smaller τ_e, as shown in Figure 71.

In this way, some regions of the network may have a smaller one-hop delay when $n = \tau$ with the comprehensive strategy, as shown in Figure 72. This reason has been explained in Figure 30.

After using the comprehensive strategy optimization, the one-hop delay and the number of hops at different distance in the network are less than or equal to the effect of the strategy 2 optimization, so the end-to-end delay optimized by the comprehensive strategy is not greater than the result obtained by the strategy 2, as shown in Figure 73.

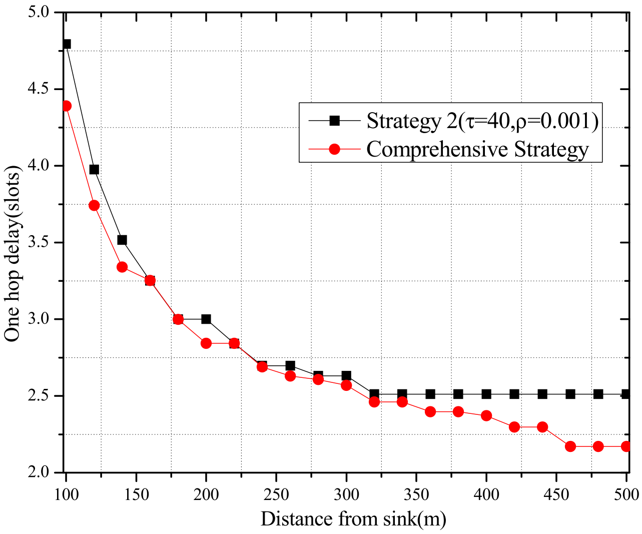

FIGURE 72. **Comparison of one hop delay after strategy 2 and comprehensive strategy optimization.**

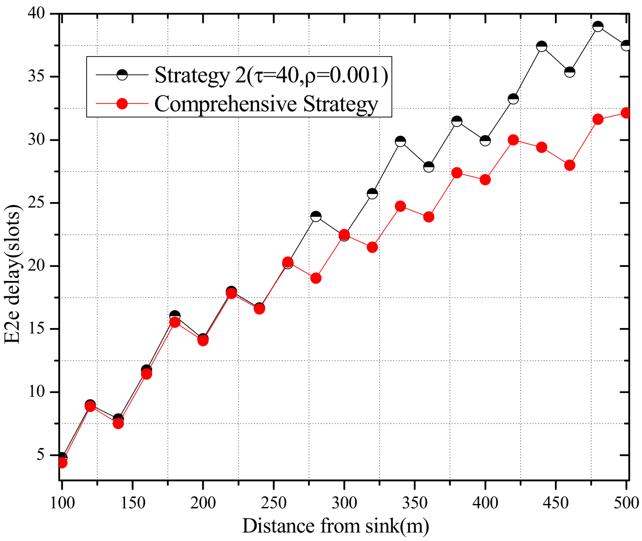

FIGURE 73. **Comparison of end-to-end delay optimized by Strategy 2 and Comprehensive Strategy.**

Especially, in the farther distance from the sink, the optimization of the end-to-end delay is significant due to the reduction in the number of hops. For example, the end-to-end delay at $L = 460$m is 20.86% shorter than strategy 2, which is 53.43% shorter than the original network.

In sparse networks, the residual energy in the far sink region is better utilized than that in strategy 2, as shown in Figure 74.

In our previous analysis, the energy consumption of nodes in a unit time is given. When the network dies, the energy consumption is actually energy consumption per unit time multiplied by time. This will not affect the calculation of energy utilization rate, so we use the energy consumption per unit time to calculate the energy utilization rate of the network. As shown in Figure 75, in the dense network with

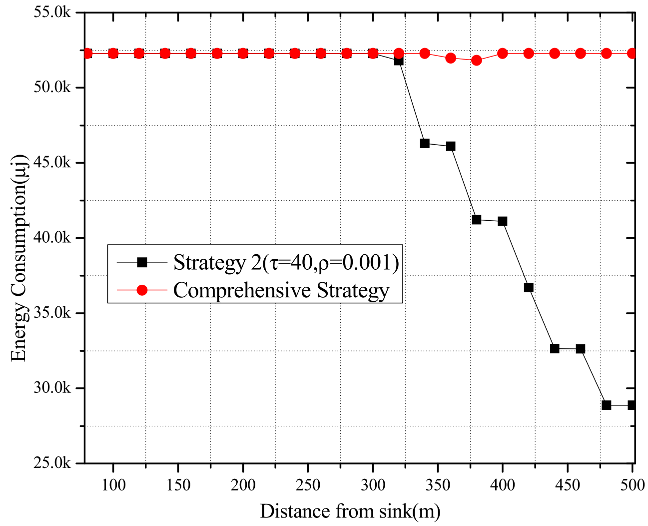

FIGURE 74. **Energy consumption comparison.**

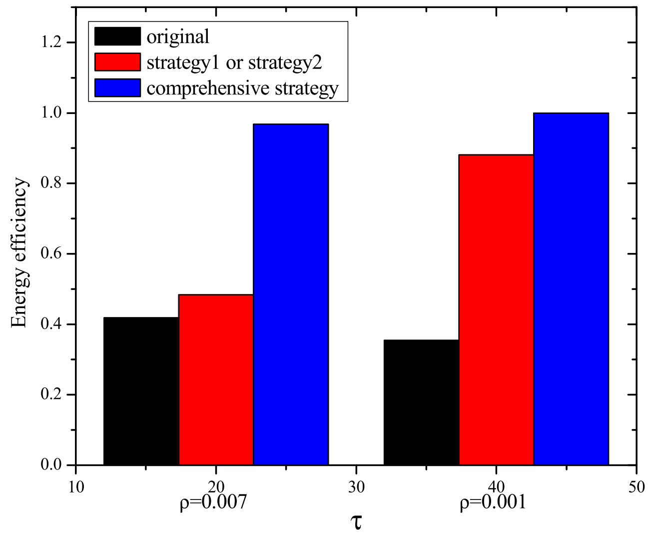

FIGURE 75. **Comparison of energy utilization rate.**

$\tau = 20$ and $\rho = 0.007$, the energy utilization ratio of the original network is 41.8%. After using strategy 1 and comprehensive strategy optimization, the energy utilization ratio reaches 48.3% and 96.7%, respectively. In the sparse network with $\tau = 40$ and $\rho = 0.001$, the energy utilization ratio of the original network is 35.4%. After using strategy 2 and comprehensive strategy optimization, the energy utilization ratio reaches 88.1% and 99.9% respectively.

VII. CONCLUSION

In WSNs with duty cycle operation, when the nodes communicate with each other, both the receiver and the sender need to be awake at the same time. There are two ways to achieve this goal: synchronous and asynchronous. Although the synchronization method can improve some network performance, the network synchronization mechanism is a system operation that runs continuously during the lifetime of the network, which will consume a lot of network resources. Besides, if multiple adjacent nodes send data at the same time, a corresponding fallback mechanism is required. Based on these considerations, an asynchronous model is used in this paper to analyze the energy efficiency and transmission delay.

In the traditional wireless sensor networks, the information is transmitted to the central control node in a multi-hop manner, and a high end-to-end delay is generated in the transmission process. In practical applications, WSNs are often required to have higher real-time performance. So how to effectively reduce the routing delay is an urgent problem to be solved. Moreover, due to the characteristics of data aggregation of WSNs, at the end of network life, the residual energy of nodes farther away from sink is more, and the energy utilization of the network is not high. In this paper, under the slot model, we first study the key factors affecting the one-hop delay: the ratio of the number of candidate nodes n to the number of slots per cycle τ. For networks with different value of $^{n}/_{\tau}$, we propose two solutions. For dense networks, the region of candidate nodes is limited by setting the minimum forward distance r_0, which reduces the number of candidate nodes and the number of hops. For sparse networks, we use the residual energy in the far sink region to increase the duty cycle of nodes, which reduces the number of slots per cycle τ. By using the two schemes, we gain a smaller end-to-end delay, and scheme 2 also effectively improves the energy utilization of the network. Finally, we propose a comprehensive strategy by combing strategy 1 and 2, which uses the same processing method in networks with any ratio of $^{n}/_{\tau}$, and can achieve lower end-to-end delay and higher energy utilization than scheme 1 or scheme 2. Experiments show that the comprehensive strategy better performance and universal applicability.

REFERENCES

[1] W. Wei, H. Song, W. Li, P. Shen, and A. Vasilakos, "Gradient-driven parking navigation using a continuous information potential field based on wireless sensor network," *Inf. Sci.*, vol. 408, pp. 100–114, Oct. 2017.

[2] Z. Li, Y. Liu, A. Liu, S. Wang, and H. Liu, "Minimizing convergecast time and energy consumption in green Internet of Things," *IEEE Trans. Emerg. Topics Comput.*, to be published. doi: 10.1109/TETC.2018.2844282.

[3] Y. Liu, M. Ma, X. Liu, N. Xiong, A. Liu, and Y. Zhu, "Design and analysis of probing route to defense sink-hole attacks for Internet of Things Security," *IEEE Trans. Netw. Sci. Eng.*, to be published. doi: 10.1109/TNSE.2018.2881152.

[4] H. Teng *et al.*, "A novel code data dissemination scheme for Internet of Things through mobile vehicle of smart cities," *Future Gener. Comput. Syst.*, vol. 94, pp. 351–367, May 2019.

[5] X. Luo, C. Jiang, W. Wang, Y. Xu, H. Wang, and W. Zhao, "User behavior prediction in social networks using weighted extreme learning machine with distribution optimization," *Future Gener. Comput. Syst.*, vol. 93, pp. 1023–1035, Apr. 2019.

[6] T. Li, K. Ota, T. Wang, X. Li, Z. Cai, and A. Liu, "Optimizing the coverage via the UAVs with lower costs for information-centric Internet of Things," *IEEE Access*, vol. 7, pp. 15292–15309, 2019.

[7] W. Wei, J. Su, H. Song, H. Wang, and X. Fan, "CDMA-based anti-collision algorithm for EPC global C1 Gen2 systems," *Telecommun. Syst.*, vol. 67, no. 1, pp. 63–71, Jan. 2019.

[8] J. Ren, Y. Zhang, K. Zhang, A. Liu, J. Chen, and X. S. Shen, "Lifetime and energy hole evolution analysis in data-gathering wireless sensor networks," *IEEE Trans. Ind. Informat.*, vol. 12, no. 2, pp. 788–800, Apr. 2016.

[9] X. Ju, W. Liu, C. Zhang, A. Liu, T. Wang, N. N. Xiong, and Z. Cai, "An energy conserving and transmission radius adaptive scheme to optimize performance of energy harvesting sensor networks," *Sensors*, vol. 18, no. 9, p. 2885, 2018. doi: 10.3390/s18092885.

[10] M. Huang, A. Liu, N. Xiong, T. Wang, and A. V. Vasilakos, "A low-latency communication scheme for mobile wireless sensor control systems," *IEEE Trans. Syst., Man, Cybern. Syst.*, vol. 49, no. 2, pp. 317–332, Feb. 2019.

[11] J. Tan *et al.*, "A low redundancy data collection scheme to maximize lifetime using matrix completion technique," *EURASIP J. Wireless Commun. Netw.*, vol. 2019, no. 1, p. 5, Dec. 2019. doi: 10.1186/s13638-018-1313-0.

[12] Z. Li, J. Gui, N. Xiong, and Z. Zeng, "Energy-efficient resource sharing scheme with Out-band D2D relay-aided communications in C-RAN-based underlay cellular networks," *IEEE Access*, vol. 7, pp. 19125–19142, 2019.

[13] J. Ren, Y. Zhang, N. Zhang, D. Zhang, and X. Shen, "Dynamic channel access to improve energy efficiency in cognitive radio sensor networks," *IEEE Trans. Wireless Commun.*, vol. 15, no. 5, pp. 3143–3156, May 2016.

[14] X. Deng *et al.*, "Cooperative channel allocation and scheduling in multi-interface wireless mesh networks," *Peer-Peer Netw. Appl.*, vol. 12, no. 1, pp. 1–12, Jan. 2019.

[15] J. Tan *et al.*, "An adaptive collection scheme based matrix completion for data gathering in energy-harvesting wireless sensor network," *IEEE Access*, vol. 7, no. 1, pp. 6703–6723, 2019.

[16] J. Gui, Z. Li, and Z. Zeng, "Improving energy-efficiency for resource allocation by relay-aided in-band D2D communications in C-RAN-based systems," *IEEE Access*, vol. 7, pp. 8358–8375, 2018.

[17] W. Qi *et al.*, "Minimizing delay and transmission times with long lifetime in code dissemination scheme for high loss ratio and low duty cycle wireless sensor networks," *Sensors*, vol. 18, no. 10, p. 3516, 2018. doi: 10.3390/s18103516.

[18] H. Teng, W. Liu, T. Wang, A. Liu, X. Liu, and S. Zhang, "A cost-efficient greedy code dissemination scheme through vehicle to sensing devices (V2SD) communication in smart city," *IEEE Access*, vol. 7, pp. 16675–16694, 2019.

[19] Y. Ren, W. Liu, T. Wang, X. Li, N. N. Xiong, and A. Liu, "A collaboration platform for effective task and data reporter selection in crowdsourcing network," *IEEE Access*, vol. 7, pp. 19238–19257, 2019.

[20] H. Zhou, S. Xu, D. Ren, C. Huang, and H. Zhang, "Analysis of event-driven warning message propagation in vehicular ad hoc networks," *Ad Hoc Netw.*, vol. 55, pp. 87–96, Feb. 2017.

[21] B. Huang, W. Liu, T. Wang, X. Li, H. Song, and A. Liu, "Deployment optimization for data centers in vehicular networks," *IEEE Access*, vol. 7, no. 1, pp. 20644–20663, 2019.

[22] C. Zhou, Y. Gu, S. He, and Z. Shi, "A robust and efficient algorithm for coprime array adaptive beamforming," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1099–1112, Feb. 2017.

[23] Q. Deng *et al.*, "Compressed sensing for image reconstruction via back-off and rectification of greedy algorithm," *Signal Process.*, vol. 157, pp. 280–287, Apr. 2019.

[24] M. Huang, W. Liu, T. Wang, H. Song, X. Li, and A. Liu, "A queuing delay utilization scheme for on-path service aggregation in services oriented computing networks," *IEEE Access*, vol. 7, pp. 23816–23833, 2019.

[25] X. Liu, S. Wu, X. Xu, J. Jiao, and Q. Zhang, "Improved polar SCL decoding by exploiting the error correction capability of CRC," *IEEE Access*, vol. 7, pp. 7032–7040, 2019.

[26] M. Chen, Y. Li, X. Luo, W. Wang, L. Wang, and W. Zhao, "A novel human activity recognition scheme for smart health using multilayer extreme learning machine," *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2018.2856241.

[27] X. Xiang, W. Liu, N. N. Xiong, H. Song, A. Liu, and T. Wang, "Duty cycle adaptive adjustment based device to device (D2D) communication scheme for WSNs," *IEEE Access*, vol. 6, pp. 76339–76373, 2018.

[28] K. P. Naveen and A. Kumar, "Relay selection for geographical forwarding in sleep-wake cycling wireless sensor networks," *IEEE Trans. Mobile Comput.*, vol. 12, no. 3, pp. 475–488, Mar. 2013.

[29] Y. Liu *et al.*, "FFSC: An energy efficiency communications approach for delay minimizing in Internet of Things," *IEEE Access*, vol. 4, pp. 3775–3793, 2016.

[30] C. Xu, J. Ren, D. Zhang, Y. Zhang, Z. Qin, and K. Ren, "GANobfuscator: Mitigating information leakage under GAN via differential privacy," *IEEE Trans. Inf. Forensics Secur.*, to be published. doi: 10.1109/TIFS.2019.2897874.

[31] W. Yang *et al.*, "Adding active slot joint larger broadcast radius for fast code dissemination in WSNs," *Sensors*, vol. 18, no. 11, p. 4055, Nov. 2018. doi: 10.3390/s18114055.

[32] M. Huang, A. Liu, M. Zhao, and T. Wang, ''Multi Working Sets Alternate Covering Scheme for Continuous Partial Coverage in WSNs,'' *Peer-to-Peer Netw. Appl.*, vol. 12, no. 3, pp. 553–567, May 2019. doi: 10.1007/s12083-018-0647-z.
[33] A. Liu, J. Min, K. Ota, and M. Zhao, ''Reliable differentiated services optimization for network coding cooperative communication system,'' *Int. J. Comput. Syst. Sci. Eng.*, vol. 33, no. 4, pp. 235–250, Jul. 2018.
[34] J. So and H. Byun, ''Load-balanced opportunistic routing for duty-cycled wireless sensor networks,'' *IEEE Trans. Mobile Comput.*, vol. 16, no. 7, pp. 1940–1955, Jul. 2017.
[35] S. Zhang, K.-K. R. Choo, Q. Liu, and G. Wang, ''Enhancing privacy through uniform grid and caching in location-based services,'' *Future Gener. Comput. Syst.*, vol. 86, pp. 881–892, Sep. 2018.
[36] J. Gui and K. Zhou, ''Cellular throughput optimization by game-based power adjustment and outband D2D communication,'' *EURASIP J. Wireless Commun. Netw.*, vol. 2018, p. 254, Oct. 2018. doi: 10.1186/s13638-018-1275-2.
[37] C. Yang, Z. Shi, K. Han, J. Zhang, Y. Gu, and Z. Qin, ''Optimization of particle CBMeMBer filters for hardware implementation,'' *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 9027–9031, Sep. 2018. doi: 10.1109/TVT.2018.2853120.
[38] T. Wang, G. Zhang, A. Liu, M. Z. A. Bhuiyan, and Q. Jin, ''A secure IoT service architecture with an efficient balance dynamics based on cloud and edge computing,'' *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2018.2870288.
[39] Y. Liu, A. Liu, X. Liu, and X. Huang, ''A statistical approach to participant selection in location-based social networks for offline event marketing,'' *Inf. Sci.*, vol. 480, pp. 90–108, Apr. 2019.
[40] L. Zhou, X. Li, K.-H. Yeh, C. Su, and W. Chiu, ''Lightweight IoT-based authentication scheme in cloud computing circumstance,'' *Future Gener. Comput. Syst.*, vol. 91, pp. 244–251, Feb. 2019.
[41] X. Liu, Y. Liu, N. Zhang, W. Wu, and A. Liu, ''Optimizing trajectory of unmanned aerial vehicles for efficient data acquisition: A matrix completion approach,'' *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2019.2894257.
[42] J. Li *et al.*, ''Battery-friendly relay selection scheme for prolonging the lifetimes of sensor nodes in the Internet of Things,'' *IEEE Access*, vol. 7, pp. 33180–33201, 2019. doi: 10.1109/ACCESS.2019.2904079.
[43] X. Xiang, W. Liu, A. Liu, N. Xiong, Z. Zeng, and Z. Cai, ''Adaptive duty cycle control–based opportunistic routing scheme to reduce delay in Cyber physical systems,'' *Int. J. Distrib. Sensor Netw.*, vol. 18, no. 4, p. 1216, Apr. 2018. doi: 10.1177/1550147719841870.
[44] J. Ren, H. Guo, C. Xu, and Y. Zhang, ''Serving at the edge: A scalable IoT architecture based on transparent computing,'' *IEEE Netw.*, vol. 31, no. 5, pp. 96–105, Aug. 2017.
[45] W. Liu, P. Zhuang, H. Liang, J. Peng, and Z. Huang, ''Distributed economic dispatch in microgrids based on cooperative reinforcement learning,'' *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 29, no. 6, pp. 2192–2203, Jun. 2018.
[46] C. Zhang, Y. Lin, L. Zhu, A. Liu, Z. Zhang, and F. Huang, ''CNN-VWII: An efficient approach for large-scale video retrieval by image queries,'' *Pattern Recognit. Lett.*, vol. 123, pp. 82–88, May 2019.
[47] Y. Liu, A. Liu, N. N. Xiong, T. Wang, and W. Gui, ''Content propagation for content-centric networking systems from location-based social networks,'' *IEEE Trans. Syst. Man Cybern.-Syst.*, to be published. doi: 10.1109/TSMC.2019.2898982.
[48] M. Luo, K. Wang, Z. Cai, A. Liu, Y. Li, and C. F. Cheang, ''Using imbalanced triangle synthetic data for machine learning anomaly detection,'' *Comput., Mater. Continua*, vol. 58, no. 1, pp. 15–26, Jan. 2019.
[49] H. Xiong, H. Zhang, and J. Sun, ''Attribute-based privacy-preserving data sharing for dynamic groups in cloud computing,'' *IEEE Syst. J.*, to be published. doi: 10.1109/JSYST.2018.2865221.
[50] T. Wang, J. Zhou, A. Liu, M. Z. A. Bhuiyan, G. Wang, and W. Jia, ''Fog-based computing and storage offloading for data synchronization in IoT,'' *IEEE Internet Things J.*, to be published. doi: 10.1109/JIOT.2018.2875915.
[51] S. Zhang, X. Li, Z. Tan, T. Peng, and G. Wang, ''A caching and spatial K-anonymity driven privacy enhancement scheme in continuous location-based services,'' *Future Gener. Comput. Syst.*, vol. 94, pp. 40–50, May 2019.
[52] W. Zhang *et al.*, ''Adaption resizing communication buffer to maximize lifetime and reduce delay for WVSNs,'' *IEEE Access*, vol. 7, pp. 48266–48287, 2019. doi: 10.1109/ACCESS.2019.2909869.
[53] Z. Zhu *et al.*, ''Fair resource allocation for system throughput maximization in mobile edge computing,'' *IEEE Access*, vol. 6, pp. 5332–5340, 2018.
[54] T. Wang, Y. Liang, W. Jia, M. Arif, A. Liu, and M. Xie, ''Coupling resource management based on fog computing in smart city systems,'' *J. Netw. Comput. Appl.*, vol. 135, pp. 11–19, Jun. 2019.
[55] Y. Liu, A. Liu, N. Zhang, X. Liu, M. Ma, and Y. Hu, ''DDC: Dynamic duty cycle for improving delay and energy efficiency in wireless sensor networks,'' *J. Netw. Comput. Appl.*, vol. 131, pp. 16–27, Jan. 2019.
[56] L. Carr-MotyčkováÂĄ and D. Dryml, ''Convergecast tree construction in wireless sensor networks,'' *Adhoc Sensor Wireless Netw.*, vol. 27, nos. 3–4, pp. 263–293, 2015.
[57] H. Byun, S. Son, and J. So, ''Queue management based duty cycle control for end-to-end delay guarantees in wireless sensor networks,'' *Wireless Netw.*, vol. 19, no. 6, pp. 1349–1360, 2013.
[58] Z. Chen, A. Liu, Z. Li, Y. J. Choi, and J. Li, ''Distributed duty cycle control for delay improvement in wireless sensor networks,'' *Peer-to-Peer Netw. Appl.*, vol. 10, no. 3, pp. 559–578, May 2017.
[59] Y. Liu, A. Liu, and Z. Chen, ''Analysis and improvement of send-and-wait automatic repeat-request protocols for wireless sensor networks,'' *Wireless Pers. Commun.*, vol. 81, no. 3, pp. 923–959, 2015.

FEIHU WANG is currently pursuing the master's degree with the School of Computer Science and Engineering, Central South University, China. His research interests include crowd sensing networks and wireless sensor networks.

WEI LIU received the Ph.D. degree in computer application technology from Central South University, China, in 2014. He is currently an Associate Professor and Senior Engineer with the School of Informatics, Hunan University of Chinese Medicine, China. His research interests include software engineering, data mining, and medical informatics. He has published over 20 papers in the above related fields.

TIAN WANG received the B.Sc. and M.Sc. degrees in computer science from the Central South University, in 2004 and 2007, respectively, and the Ph.D. degree from the City University of Hong Kong, in 2011. He is currently an Associate Professor with Huaqiao University. His research interests include wireless sensor networks, social networks, and mobile computing.

MING ZHAO received M.Sc. and Ph.D. degrees in computer science from Central South University, China, in 2003 and 2007, respectively, where he is currently a Professor with the School of Software. His major research interest is wireless networks. He is also a member of the China Computer Federation (CCF).

MANDE XIE was born in 1977. He received the Ph.D. degree in circuit and system from Zhejiang University, in 2006. He is currently a Professor with Zhejiang Gongshang University. His research interests include wireless sensor networks (WSNs), social networks, and privacy preservation.

HOUBING SONG (M'12–SM'14) received the Ph.D. degree in electrical engineering from the University of Virginia, Charlottesville, VA, USA, in 2012.

In 2017, he joined the Department of Electrical, Computer, Software, and Systems Engineering, Embry-Riddle Aeronautical University, Daytona Beach, FL, USA, where he is currently an Assistant Professor and the Director of the Security and Optimization for Networked Globe Laboratory (SONG Lab, www.SONGLab.us). He served on the Faculty of West Virginia University, from 2012 to 2017. In 2007, he was an Engineering Research Associate with the Texas A&M Transportation Institute. He is the author of more than 100 articles. His research interests include cyber-physical systems, cybersecurity and privacy, the Internet of things, edge computing, big data analytics, unmanned aircraft systems, connected vehicle, smart and connected health, and wireless communications and networking.

Dr. Song is a senior member of ACM. He was a very first recipient of the Golden Bear Scholar Award, and the highest campus-wide recognition for research excellence at West Virginia University Institute of Technology (WVU Tech), in 2016. He serves as an Associate Technical Editor for the IEEE *Communications Magazine*. He is the Editor of four books, including *Smart Cities: Foundations, Principles and Applications* (Hoboken, NJ: Wiley, 2017), *Security and Privacy in Cyber-Physical Systems: Foundations, Principles and Applications* (Chichester, UK: Wiley-IEEE Press, 2017), *Cyber-Physical Systems: Foundations, Principles and Applications* (Boston, MA: Academic Press, 2016), and *Industrial Internet of Things: Cybermanufacturing Systems* (Cham, Switzerland: Springer, 2016).

XIONG LI received the master's degree in mathematics and cryptography from Shaanxi Normal University (SNNU), China, in 2009, and the Ph.D. degree in computer science and technology from the Beijing University of Posts and Telecommunications (BUPT), China, in 2012. He is currently an Associate Professor with the School of Computer Science and Engineering, Hunan University of Science and Technology (HNUST), China. He has published more than 70 refereed journal papers in his research interests, which include cryptography, information security, and cloud computing security. He has served as a TPC member of several international conferences on information security and a reviewer for more than 30 ISI indexed journals. He was a recipient of the *Journal of Network and Computer Applications* 2015 Best Research Paper Award. He is currently an Editor of *Telecommunication Systems* and *KSII Transactions on Internet and Information Systems*.

ANFENG LIU received the M.Sc. and Ph.D. degrees in computer science from Central South University, China, in 2002 and 2005, respectively, where he is currently a Professor of the School of Information Science and Engineering. His major research interest is wireless sensor networks. He is also a member (E200012141M) of the China Computer Federation (CCF).