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Adaptive Contention Window MAC Protocol in a Global View for Emerging Trends Networks

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ABSTRACT Massive tremendous amount of miniaturized wireless Internet of Things (IoT) devices are widely employed in many fields such as industrial production, social life, public (and defense) security and management of human society. The limitation of node device's energy capacity is the bottleneck issue of these network systems. MAC protocol is a key communication protocol for such sensor nodes which both rationally saves energy (an alternative to energy harvesting way) and improves the performances of the wireless sensor networks. There are complex tradeoff optimization relationships between the size of contention window and energy consumption, delay and collision, in which too large or too small contention window value cannot make the network performance optimal. This paper firstly gives an optimization algorithm for the size of the contention window through theoretical analysis, which can achieve a compromise between energy consumption (i.e. alternative energy harvesting) and delay. Then, a global view based adaptive contention window (GV-ACW) MAC protocol is proposed to further reduce latency and improve alternative energy harvesting. The GV-ACW MAC protocol adopts the optimized size of contention window in the near sink area to meet the functional requirements of data forwarding, while in the far sink area, the size of contention window is larger than it required by node for data transmission so as to reduce the latency and thereby improve the network performance as a whole. The theoretical analysis and experimental results show that, comparing with previous MAC protocol, GV-ACW protocol can realize effective alternative energy harvesting which resulting increasement of the network lifetime by 6% and reduce the network delay by 15%.

INDEX TERMS Wireless sensor networks, alternative energy harvesting, size of contention window, delay, lifetime, Internet of Things.

I. INTRODUCTION

Internet of things (IoT) [1]–[3] makes use of sensor devices widely deployed or existing in various equipment to realize information collection at low cost, which provides a new solution for the major requirements of complex sensing applications in the key infrastructure such as monitoring systems [4], [5], intelligent traffic management and automatic vehicles in traffic environment [6]–[8] and weather surveillance platform. Significant advancements in the Internet of Things (IoT) have generated various opportunities in the field of healthcare [8], [9]. At present, various human health and medical equipment have been developed, such as the devices monitoring human vital life signs [10], [11]. These devices can be massively distributed in hospitals and other large-scale internal environments, forming wireless sensor networks (WSNs) [10]. There are also wearable devices deployed on the human body forming the Wireless Body Area Networks (WBANs) [12]. Most sensor nodes use wireless communication to complete the perception of the surrounding environments by collaborative communication [13], [14], so an effective communication protocol is of great significance to the promotion of the smart healthcare [15]–[17]. The protocol of MAC is a basic protocol for WSNs and has an important impact on the network performance [18]. The size of Contention Window (CW) is the crucial element for MAC

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protocol [19], [21], which also has a great impact on many performance evaluation parameters like packet loss probability, end-to-end delay, delay jitter, link utilization, throughput and energy consumption [19], which is particularly significant for Internet of Things (IoT) [20], [21], so optimizing CW is necessary.

There exit many schemes proposed for improving MAC protocol [18]–[21]. Among them, adjusting the size of the contention window to optimize the network performance is one of the important methods [19]–[21]. The earlier research mainly uses the optimized contention window, but once the window size is determined it no longer changes. However, the latest research adopts the adaptive contention window size, which can be adjusted adaptively according to the network status [19]–[21], so its performance is better than the method of fixed window size. However, according to the existing research, most of the proposed protocols perform optimizing the contention window size only from the state of nodes themselves instead of the global perspective of the network, whose result is not optimal. In fact, there are some differences in the impact of CW size on various indicators. For example, in WSNs, the energy consumption of nodes in working mode is 1000 times higher than that in sleeping mode. Therefore, in order to save energy, nodes are supposed to be kept in sleeping mode as much as possible [22]. In addition, the sensor nodes generally adopt the duty cycle, that is, the nodes periodically wake and sleep [22], [23]. The awake time is composed of multiple different working states, one of which is the CW time [19]–[22]. Therefore, if the CW time is larger, the awake time of nodes is relatively longer, which makes the energy consumption larger than that of nodes with small CW [19]. When the CW becomes smaller, the awake time and the energy consumption is reduced. However, the reduction of CW may lead to an increase in the probability of packet retransmission and the rate of packet loss, resulting in the increased energy consumption because of data retransmission is greater than the energy savings due to the reduction of CW [19], [20]. Therefore, how to obtain the optimal CW size is an issue worth studying. But from a global perspective, even if each node obtains the optimized CW size, it still cannot achieve the optimal effect from the global perspective of the network. For example, due to the unbalanced energy consumption in the network, for a node with energy surplus, a CW value greater than the optimized result brings more energy consumption, so the surplus energy can be further used and the delay is reduced. Therefore, it can be seen that the optimization results obtained from the global optimization perspective are quite different from the previous studies, which is worthy of further study.

In this article, a global view based adaptive contention window (GV-ACW) MAC protocol is proposed to alternatively ''harvest'' energy resulting improvement of the network life and to reduce the communication delay. The main innovations of this work are as follows:

(1) By analyzing the relationship between the size of the contention window and the network performance indicators, an optimization algorithm is proposed, which helps to select the appropriate contention window size to improve the performance of the network.

Through the analysis, it is found that there is a complex optimization relationship between the contention window size, the energy consumption and the transmission delay. When the contention window is large, the communication conflicts between nodes can be reduced, thus the delay is reduced. At the same time, it will decrease the energy consumption due to less data retransmission, but on the other hand it needs to consume more energy to maintain a large contention window. Conversely, when the contention window is small, the data collision rate will increase, leading to more energy consumption of data retransmission, and the delay is also increased. However, from another perspective, the energy consumption of the node for maintaining the window is reduced. In addition, a small window size will also make the preamble time required before the data transmission shorter and can reduce some delay. Based on the above analysis and research, this paper theoretically gives the relationship between various performance indicators and the size of CW, and an optimization algorithm is designed for the selection of size of the contention window, which leads to effective alternative energy harvesting for the wireless sensor networks as a whole.

(2) An adaptive contention window protocol based on global view is proposed, which can effectively improve the network performance.

Reducing energy consumption which means energy harvesting in substitution is an important consideration in the design of the MAC protocol. From the global perspective of WSNs, the energy consumption of nodes closer to the sink node is much higher than that in the far sink area (i.e. hotspots), because the nodes near the sink undertake much more data. Therefore, according to relevant research, although the energy consumption of nodes in the near sink area is tense, the energy remaining rate of the nodes far from the sink is as high as 90% [24]–[26]. Consequently, from a global perspective, when determining the CW size of nodes at the edge, it does not need to consider too much on their energy consumption, but mainly optimizes the network communication performance, including data conflict rate, packet loss rate and delay. In this way, the network energy has been fully utilized, and the communication performance has been effectively improved as well.

(3) Through detailed theoretical analysis and simulation experiments, it is confirmed that the strategy proposed in this paper has good performance and effectiveness. By saving and rationally utilizing energy of the nodes in the area of near or far from sink node, the proposed Global View based Adaptive Contention Window (GV-ACW) MAC protocol can efficiently obtain alternative energy harvesting leading to increasement of the network lifetime by 6% while reducing the delay by more than 15%.

The rest of this paper is organized as follows. In Section 2, the related works are reviewed. The system model and problem statement is described in Section 3. In Section 4, the details of global view of adaptive contention window (GV-ACW) MAC protocol are presented. Performance analysis is provided in Section 5. Section 6 is the analysis and comparison of experimental results. We conclude our work in Section 7.

II. RELATED WORK

Due to the development of microprocessor technology, there are more and more devices connected to the Internet of Thing [26], [27]. According to the estimation of researchers, the number of devices connected to IoT has exceeded 20 billion, which is rapidly increasing [28], [29]. Most of these IoT devices have the ability to perceive data, thereby achieving the goal of sensing the world [30], [31]. Based on the online Rewards-optimal Auction (RoA), paper [32] studied the computation offloading and scheduler which is composed of mobile devices (MD) supporting energy harvesting for edge computing systems. In order to solve the problem of the energy shortage of the Internet of Things, literature [33] proposed a green IoT network based on the Lyapunov framework that harvest energy from environmental energy and the grid, and the network transmits data through access to the licensed spectrum. A large number of IoT devices are mostly located at the edge of the network forming an edge network [34]–[36], which transfers the computing center from the cloud to the edge of the network, called edge computing. And it is integrated with artificial intelligence technology [30], [37], security [38], [39] and privacy protection technology [35], which makes its development present an accelerated trend. Aiming at the sustainable resource allocation problem of hybrid energy (HES) driving cloud radio access network (CRAN), [36] studied radio units (RU) powered by grid energy and energy harvested from green sources and allocated channels to achieve links. It also proposes a net gain optimal resource allocation (GRA) algorithm, which effectively improves the sustainability of the battery. The healthcare monitoring devices are basically self-organized to a network in the form of wireless collaborative perception and communication. The MAC protocol is one of the most important protocols in the network [18]–[21]. By weighting and optimizing the mixed cost of time and energy consumption, article [39] explored the method of minimizing the mixed cost of time and energy (MOTE). Simulation experiments show that compared with similar strategies, their algorithm can always achieve the smallest mixed overhead of time and energy (MOTE). According to the different mechanisms for controlling collision avoidance at the data link layer, it is divided into contention, contention-free and hybrid type [40], [41]. In the contention MAC protocol, the sensor nodes in the monitoring area share the same medium and then preempt the only channel through contending the medium. Then the node getting the channel can transmit the data. At present, the mature contention MAC protocols include S-MAC [42], T-MAC [43] and SIFT [44]. In the contention-free MAC protocol, when the communicating nodes share the same medium, the channel is divided into many sub-channels by techniques such as time division multiplexing, code division multiplexing or frequency division multiplexing. And then the nodes select different sub-channels according to different multiplexing technologies for information forwarding. In this way, the sensor nodes can communicate without affecting other nodes, thereby avoiding data conflicts. The existing mature contention-free MAC protocols include DEANA [45], LMAC [46], [47] and TRANMA [48]. In the hybrid MAC protocol, based on the actual situation, two or more types of the contention and contention-free MAC protocols are combined across layers.

Wei Ye and John Heidemann of USC/ISI proposed the S-MAC protocol [42] based on PAMAS [49]. This protocol adopts three mechanisms: (a) periodic sleep and listening, which reduces the unnecessary energy consumption under the listening mode. (b) Virtual clusters are formed between nodes to maintain the scheduling table of surrounding nodes to control their scheduling information. (c) The RTS/CTS mechanism is adopted to save the large energy consumption caused by conflict failure and improve the data transmission efficiency by sending the request message first to reserve the channel. However, the main shortage of S-MAC is that in the process of communication, when a node transmits messages to another node which is just in the sleeping state, the node must wait for the next cycle to communicate, which greatly increases the network delay. It is to save energy by sacrificing time delay. Moreover, the implementation of this protocol is complicated and requires large storage space [42]. S-MAC is very scalable and suitable for the network tolerating the communication delay, and relatively has low requirements for fairness between nodes.

Dam and Koen proposed a new contention MAC protocol: T-MAC (timeout MAC) [43]. In the T-MAC protocol, the active state and the sleeping state can be changed. The data packets are mainly forwarded or received during the active state, which reduces unnecessary energy consumption by shortening the idle listening time. It applies the RTS/CTS/DATA/ACK communication mechanism, but it may cause the problem of early sleeping and increase the network delay. There are two main solutions: the first is to use the "future-request-to-send" (FRTS) mechanism, which has the advantage of reducing the data transmission delay and improving throughput. However, it increases the cost and complexity of the protocol to maintain the synchronization between the nodes. The other solution is to use the "full buffer priority" mechanism, which can control the traffic in the network, but increases the possibility of conflict when the network data is large.

In the aspect of contention window, Kyle Jamieson *et al.* [44] proposed the SIFT protocol. They found that in the traditional window based contention MAC protocol, if there is a conflict in the data communication, the node will double the CW size by back-off algorithm to reduce the possibility of collision next time. However, if the CW size is already large but fewer nodes hear and respond to the event, the delay will increase. SIFT fixes the size of the contention window, and then selects different possibility of sending messages for the time slots, so the nodes can send messages in different time slots without collision. The advantage of this protocol is that the network delay is small, but the energy consumption of nodes increases when listening to each time slot.

According to references [50]–[53], the algorithms related to the contention window can be divided into two categories: the first is adaptive while the other is adjustable. The adaptive strategy is mainly that the nodes self-adjust the contention window according to the surrounding information or the network state. However, the adjustable type is to increase or decrease the window size based on the existing basic algorithms. The main related algorithms of the two categories are introduced below.

A BEB algorithm is proposed in reference [51], but the algorithm is mainly for wired networks. For WSNs, the situation in wireless networks is different, so the BEB algorithm is supposed to be improved to adapt to WSNs. Therefore, an improved MILD algorithm based on BEB is proposed in reference [41], whose process is as follows: when nodes conflict, the contention window size will double, otherwise it decreases. Although it improves the fairness of the nodes to some extent, when the window size is doubled even if there is no conflict in the future, the contention window will not decrease and always be at a large value, which increases the network delay.

Kwon *et al.* proposed a FCR algorithm in reference [52]. In WSNs, not all nodes participate in the transmission contention, so in this algorithm not all the nodes are redistributed to contend. In this way, nodes can choose to send data without conflict in a small contention window as much as possible, and other nodes use binary exponential to reduce the slot counter in the continuous idle slots. It can effectively solve the problem of data collision, but it affects the fairness [53].

Bononi *et al.* [54] proposed a DCC algorithm, which mainly adjusts the minimum contention window based on the optimal ratio of conflict time and idle time in the network. The analysis of Bianchi *et al.* [49] shows that when the network is congested, increasing the contention window can reduce conflicts and improve the network throughput, while inappropriately increasing the window size will reduce the network throughput when the network is idle.

To sum up, the contention window protocol mainly focuses on two aspects of performance. (a) One aspect is the communication performance, which mainly refers to packet loss probability, end-to-end delay, delay jitter, link utilization and throughput [55], [56]. (b) The other aspect is the energy consumption, which is related to the fact that sensors nodes are powered by batteries and the energy is limited, so it is required to reduce the energy consumption as much as possible to prolong the network life [57]. And the performance of these two aspects is related. Generally, the energy consumption of algorithms with better communication performance will be relatively large. Therefore, energy consumption and communication performance affect each other, which makes the design and optimization of MAC protocols in WSNs more complicated. The fairness of the protocol is supposed to be considered, but the impact on the fairness in the design of CW is small, so it is not the focus of research in this article [58].

III. NETWORK MODEL AND PROBLEM STATEMENT

A. NETWORK MODEL

The network model adopted in this paper is similar to [10], [18], [22], where sensor nodes are uniformly deployed in a circular area of radius, the density of nodes is expressed as, and the sink node is located at the center of the circular area, which is the final receiving station of information. We make the following assumptions about the network model:

(1) The sensor nodes are distributed in the network randomly and no longer move after the deployment. All sensor nodes know the relative positions of other nodes, and can sense the active state of the nodes within the sensing radius. The number of hops from this node to the sink node can be calculated through the Routing Diffusion Protocol [10], [18]. The data packets of the node are randomly generated, whose probability is . Data packets are routed to sink nodes by multi-hop routing [18], [22].

(2) The initial energy of the sensor node is, while that of the sink node has no restrictions. The energy of the node is mainly used to listen to the channel, receive data and send data. And the energy consumption of other non-primary factors can be ignored.

B. CONTENTION WINDOW MODEL

The protocol used in WSNs is 802.11. When the messages sent conflict during the contention of multiple sensor nodes for one channel, the contention window of the node changes as follows. The node firstly detects whether the channel is idle. If the time is as long as DIFS (Distributed Inter-frame Spacing), the node randomly selects a window to send messages and monitors the channel status at this time. If it is idle, the window value selected decreased by 1, and when the value is 0, the sensor node can send a message. However, when the window values of multiple nodes at this time reach 0, a conflict occurs and the nodes need to adjust the value of the contention window according to the corresponding back-off algorithm. If CW is greater than CW_{max}, it will no longer increase and be recorded as CW_{max}. Correspondingly, if it is less than CW_{min}, it will no longer decrease and maintain CW_{min}. If there is no conflict, the node can send the message directly.

The contention window is mainly composed of multiple time slots, and the unit is represented by *slot_Time*. The number of time slots is the value of the contention window. CW_{min} and CW_{max} represent the minimum and maximum value of the contention window respectively. Among them, the maximum value and the minimum value are mainly related to the physical layer, the maximum value $CW_{max} = 1023$. However, the minimum value is slightly different. For the frequency hopping network, $CW_{min} = 15$, while CW_{min} in the spread spectrum network is 63 [58].

The BEB back-off algorithm in reference [38] is used. The algorithm process is as follows. Suppose the number of competing nodes is n. Every time all nodes participate in the channel contention, the total number of back-off algorithms is m. Then the probability that node v selects the time slot as x to send is calculated by Eq. 1.

$$P_{ij} = \frac{1}{L_{ij}}, \quad i = 1, \ldots n;\ j = 0, \ldots, m. \tag{1}$$

In Eq. 1, L_{ij} is the value of CW of node i during the j^{th} back-off, and $L_{i0} = CW_{min} + 1$, $L_{im} = CW_{max} + 1$. If the back-off time selected by node u is the same as node v at this time, they will conflict and need to perform the back-off algorithm again. From the above, we know only ensure that other nodes do not choose the same back-off time, can the back-off succeed. Therefore, the following probability formula for each back-off process is as Eq. 2.

$$Pa_{ij} = C^1_{L_{ij}} * \frac{1}{L_{ij}} * \prod_{k \neq i}^{n} \left(1 - \frac{1}{L_{kj}}\right). \tag{2}$$

In the above formula, $i = 1, \ldots, n, j = 0, \ldots, m$, $k = 1, \ldots, n$. Then we use the averaging method and Eq. 2 to obtain the average value of the contention window as determined by Eq. 3 as below.

$$\bar{L} = \sum_{j=0}^{m} Pa_{ij} * L_{ij}. \tag{3}$$

In Eq. 3 above, i represents the node number. The contention window value increases in multiples. According to the above formula, it can be seen that during the contention, $\bar{L}$ will increase with the number of back-offs. In this way, the possibility of conflict is smaller and the network connectivity is better. The focus of this study is how to choose the appropriate size of contention window to optimize the network performance. To understand this paper, Table 1 gives the symbols and meanings used in this article.

C. ENERGY CONSUMPTION MODEL

Using a typical energy consumption model [15], the energy consumption of sending data is as shown in Eq. 4, and that of receiving data is in Eq. 5.

$$\begin{cases} E_{t,1}(d) = lE_{elec} + l\varepsilon_{fs}d^2 & if\ d < d_0 \\ E_{t,2}(d) = lE_{elec} + l\varepsilon_{amp}d^4 & if\ d \geqq d_0 \end{cases} \tag{4}$$

$$E_r(l) = lE_{elec}. \tag{5}$$

In the above formula, E_{elec} represents the energy consumed by the transmitting circuit. If the transmission distance is less than the threshold d_0, the free space model is applied in the power amplification loss. Instead, when the transmission distance is greater than or equal to d_0, the multipath attenuation model is used. ε_{fs}, ε_{amp} are the energy required for power amplification in the two models respectively. In Eq. 5, l represents the number of data bits. In this paper, the specific settings of the above parameters are taken from reference [15], as shown in Table 2.

TABLE 1. Abbreviations and their meanings.

Abbreviation	Meaning
R	Network radius
r	Effective transmission radius of node
ρ	Node density of network
E	Initial energy of node
ω	Probability of event occurrence
S	Packet size
H_i	The number of route hops in node i
L_{cw}	The size of the contention window for the node
φ	Packet loss rate of data in network
c	Retransmission times of nodes in network
t_s	Sleep time of nodes in a cycle
t_a	Active time of nodes in a cycle
ε_s	Energy consumption per unit time of sending node
ε_r	Energy consumption per unit time of receiving node
ε_{lpl}	Energy consumption of low function node
ε_s'	Energy consumption per unit time during sleep
$slot\_Time$	Length of time slot
L	Length of data packet
L_{ack}	Length of ACK packet
v	Rate of data transmission

TABLE 2. Network parameters.

Parameter	Value
Threshold distance (d_0) (m)	87
Sensing range (r_s) (m)	15
E_{elec} (nJ/bit)	50
e_{fs} ($pJ/bit/m^2$)	10
e_{amv} ($pJ/bit/m^4$)	0.0013
Initial energy (J)	0.5

D. PROBLEM STATEMENT

The goal of the GV-ACW MAC protocol design in this paper is to reduce energy consumption, network delay and packet loss rate, so as to ensure that the network has a longer network lifetime. The research problems in this article can be summarized as the following three aspects:

1) NETWORK LIFETIME MAXIMIZATION

According to reference [53], when a sensor node dies in the network, the connectivity performance of the network is obviously weakened. Therefore, the network lifetime is defined as the time from the start of network work to the death of first node. The initial energy of the network node is E_{ini}, and the average energy of the node k in a round of data collection is e_k, hence we get Eq. 6.

$$max\ (l) = max\left(E_{ini}/max_{1\leq k\leq n}\left(e_k\right)\right). \quad (6)$$

2) MINIMIZING DELAY

The time required for the data packet from being received by node i (expressed as n_i) to be successfully received by the next node is recorded as $\mathcal{D}_i$. While the time for data transmitted from the source node n_i to the sink is called end to end delay, which is the sum of the delay of all nodes on the routing path to the sink, as shown in Eq. 7:

$$\mathcal{D}_{i,e2e} = \sum\nolimits_{k=i}^{j} \mathcal{D}_k | n_k \in \mathcal{P}_i. \quad (7)$$

where $\mathcal{P}_i$ represents the set of nodes on the routing path from node n_i to the sink.

Therefore, the research problem of reducing delay is expressed as Eq. 8.

$$min\left(\mathcal{D}_{i,e2e}\right) = min\left(\sum\nolimits_{k=i}^{j} \mathcal{D}_k\right) | n_k \in \mathcal{P}_i. \quad (8)$$

3) MINIMIZING PACKET LOSS RATE IN THE NETWORK

When designing the MAC protocol, the packet loss rate should be as small as possible. In this model, according to the actual situation, the difference between the actual amount of data sent by nodes and that received by the sink is taken as the target function, which is recorded as $min(\mathcal{P}) = min(_{get}/_{total})$, where $_{total}$ represents the number of data packets generated in the network, and $_{get}$ is the number of packets received by the sink node.

To sum up, the comprehensive objective function is expressed as follows:

$$\begin{cases} max\ (l) = max(E_{ini}/max_{1\leq k\leq n}\left(e_k\right)) \\ min\left(\mathcal{D}_i\right) \text{ or } min\left(\mathcal{D}_{i,e2e}\right) = min\left(\sum_{k=i}^{j} \mathcal{D}_k\right) | n_k \in \mathcal{P}_i \\ \min\left(\mathcal{P}\right) = \min(_{get}/_{total}). \end{cases} \quad (9)$$

IV. THE DESIGN OF GV-ACW PROTOCOL

A. RESEARCH MOTIVATION

The research motivation of the GV-ACW protocol proposed in this article is given below:

(1) Appropriately increasing the value of the contention window of the node can reduce the delay in the network, and help to reduce the packet loss rate, thereby improving network performance. Fig. 1 and Fig. 2 show the relationship between the contention window size and network delay and packet loss rate respectively.

In Fig. 1, it can be seen from that under a certain network environment, the relationship between the contention window and the network delay is as follows: When the contention window of the node becomes larger, the delay decreases, because the probability of each node choosing the same time slot to send messages is smaller, that is, the probability of data collision is smaller. If there is data collision, the nodes will have to contend for the window again, so the delay increases greatly. Therefore, when the window size is large, although

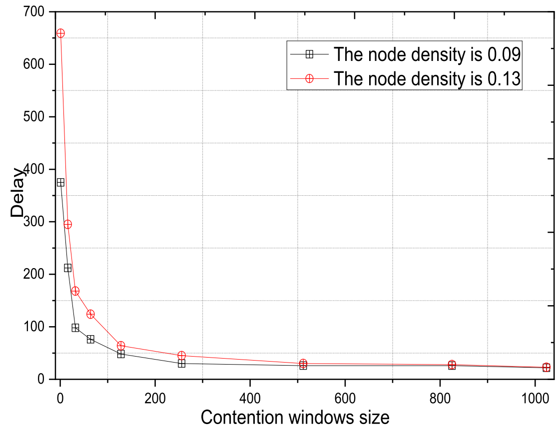

FIGURE 1. Relationship between contention window size and network delay.

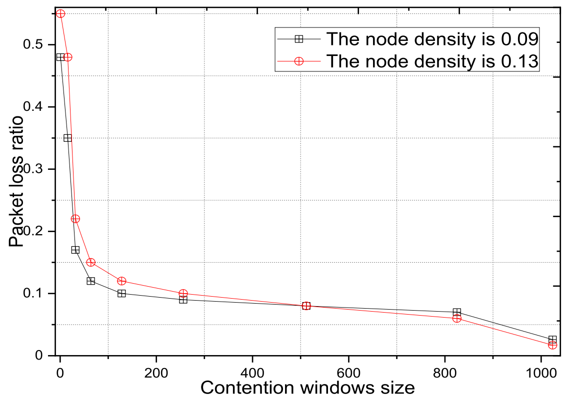

FIGURE 2. Relationship between the size of the contention window and the packet loss rate.

the nodes wait a longer time for sending slots, the waiting time is still relatively smaller than the increased delay due to the data collision. So the total delay of sending data is reduced. Conversely, when the contention window is small, each node has fewer time slots to choose for sending data, and the possibility of selecting the same time slot is greater, leading to more data collisions and more data packet retransmissions, thus the entire network delay will be increased. In addition, there is a similar relationship between the size of the contention window and the packet loss rate, that is, under certain network conditions, when the contention window becoming larger, the packet loss rate tends to decrease (see Fig. 2).

(2) With the increase of the contention window, the energy consumption of the nodes will increase to a certain extent, because the node needs to keep a larger window time.

Fig. 3 and Fig. 4 show the energy consumption of networks under different contention window sizes. Comparing Fig. 3 and Fig. 4, it can be seen that the energy consumption applying a large contention window is significantly higher than that of a smaller window. However, no matter what kind of contention window is adopted, the overall energy

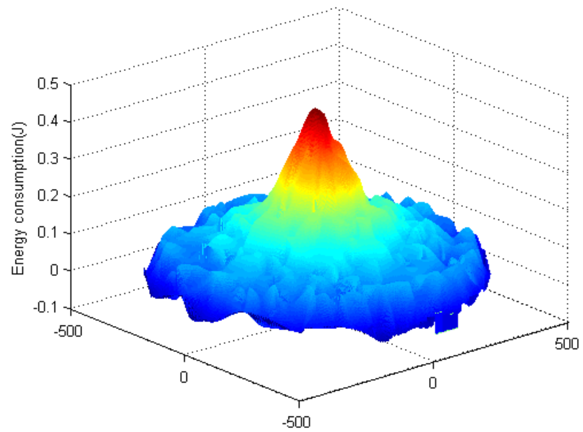

FIGURE 3. Node energy consumption of small contention window size.

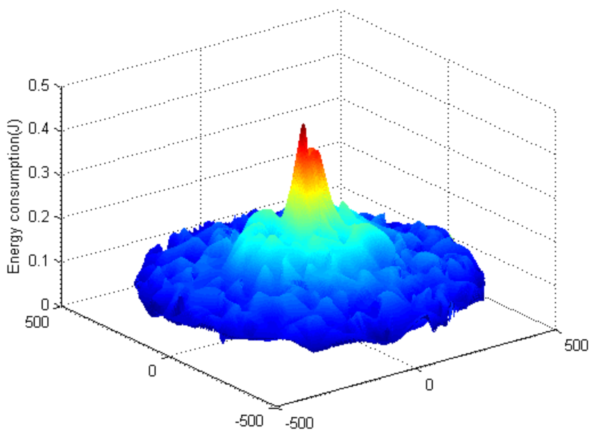

FIGURE 4. Node energy consumption of large contention window size.

consumption trend of the network is the same, that is, the energy consumption of nodes near the sink is higher, while that of nodes in the far sink area is lower. The reason for the unbalanced energy consumption is that the data collection in WSNs is a "many-to-one" mode. The nodes in the near sink area undertake much more data than the nodes at the edge, causing the more energy consumption.

From the above analysis, if the contention window is appropriately increased, the communication performance of the network will be improved, including delay and packet loss rate, but it needs to consume more energy, which may affect the lifetime of network. However, from the global view of the network, due to the unbalanced energy consumption in WSNs, there is still a large amount of residual energy in the nodes in the far sink area. Therefore, if the energy-intensive near sink area applies an optimized contention window size, and the nodes in the far sink area use the remaining energy to increase the size of the contention window of nodes, the network performance can be optimized without reducing the network lifetime. Therefore, this is the motivation for researching the GV-ACW protocol in this paper.

B. OVERVIEW OF GV-ACW PROTOCOL

The main idea of GV-ACW protocol is to make full use of the remaining energy of the nodes in the non-hotspot area to adjust the size of the contention window from the view of entire network. Therefore, this section first gives the following conclusions: In a planar network, nodes that are three hops away from the sink have sufficient energy to adjust the size of the contention window without reducing the network lifetime.

Theorem 1: in a planar wireless sensor network, if the transmission radius of the node is r, then the node with the highest energy consumption in the network is 4 times the energy consumption of the node outside the sink $3r$.

Proof: In this network, the sensing radius of the nodes is r to ensure that the nodes can receive data packets from the last routing. And the density of sensor nodes per unit length is ρ. The arc length $L_i = \theta * r * i$. In this way, the number of routing nodes on the i-th layer is $N_i = L_i * \rho$. And because the probability of event generation is ω, the event generated by this layer of routing is $N_i\omega$. Therefore, the total energy consumption of routing nodes on the i-th layer can be calculated by Eq. 10:

$$\begin{cases} E_i = E_{ir} + E_{is} \\ E_{ir} = N_{i+1}E_r \\ E_{is} = (N_{i+1} + N_i)E_s \end{cases} \tag{10}$$

where $E_{4r} = 0, E_{4s} = N_4E_s = N_4\left(lE_{elec} + l\varepsilon_{fs}d^2\right) = 4\theta r\rho\omega\left(lE_{elec} + l\varepsilon_{fs}d^2\right)$.

The average energy consumption is $\overline{E}_i = E_i/N_i$. Combining the average energy consumption formula with the above formula, the following equations can be obtained separately:

$$\begin{aligned} \overline{E}_4 &= 4\theta r\rho\omega\left(lE_{elec} + l\varepsilon_{fs}r^2\right)/(4\theta r\rho\omega), \\ \overline{E}_3 &= (4\theta r\rho\omega lE_{elec} + (lE_{elec} + l\varepsilon_{fs}r^2) \\ &\quad \times(4\theta r\rho\omega + 3\theta r\rho\omega))/(3\theta r\rho\omega), \\ \overline{E}_2 &= ((4\theta r\rho\omega + 3\theta r\rho\omega)lE_{elec} + (lE_{elec} + l\varepsilon_{fs}r^2) \\ &\quad \times(4\theta r\rho\omega + 3\theta r\rho\omega + 2\theta r\rho\omega))/(2\theta r\rho\omega), \\ \overline{E}_1 &= ((4\theta r\rho\omega + 3\theta r\rho\omega + 2\theta r\rho\omega)lE_{elec} + (lE_{elec} + l\varepsilon_{fs}r^2) \\ &\quad \times(4\theta r\rho\omega + 3\theta r\rho\omega + 2\theta r\rho\omega + \theta r\rho\omega))/(\theta r\rho\omega). \end{aligned}$$

So, we get:

$$\begin{aligned} \frac{\overline{E}_1}{\overline{E}_4} &= \frac{9E_{elec} + 10(E_{elec} + \varepsilon_{fs}r^2)}{E_{elec} + \varepsilon_{fs}r^2} > 4. \\ \frac{\overline{E}_1}{\overline{E}_3} &= \frac{9E_{elec} + 10(E_{elec} + \varepsilon_{fs}r^2)}{(4E_{elec} + 7(E_{elec} + \varepsilon_{fs}r^2)/3)} > 4. \end{aligned}$$

■

1) DESIGN IDEA OF GV-ACW PROTOCOL

In the previous existing strategies, the main consideration was how to save energy as much as possible, which is different from the GV-ACW MAC protocol. From the global view of the network, although the energy consumption of the near sink area is high, but the nodes at the edge still have surplus energy. Therefore, for the nodes with energy surplus, we are not supposed to consider too much about energy saving when designing their contention window size, but mainly consider the improvement of other network performance such as delay, packet loss rate. It can not only reduce the network performance, but also improve the network lifetime. Hence, the GV-ACW MAC protocol mainly focuses on the perspective of overall network performance optimization, and uses different contention window sizes according to the remaining energy of the nodes. From Theorem 1, the energy consumption of the nodes within one hop to the sink is the highest. Therefore, the nodes in this area adopt the optimized window size to minimize the energy consumption so as to improve the network lifetime. For nodes in the range of 2 hops from the sink, the contention window is appropriately increased. As for the node that is 3r away from the sink, its energy consumption is only 1/4 of the node within 1 hop to the sink, so there is a large amount of residual energy supporting the node to survive.

Through the analysis above, the energy consumption of layer 1 is often more than four times that of layer 3. Therefore, it is defined that the nodes within the layer 2 route adjust the size of the contention window according to the adaptive method, and the nodes outside the layer 2 route appropriately continue increasing the contention window size based on the adaptive adjustment. In this way, in the GV-ACW MAC protocol, the network is divided into two parts: (a) High energy consumption area, which is mainly the area close to the sink node. It is also proved in Theorem 1 that the energy consumption of this area (within one hop range) is more than four times that of the outside area; (b) Low energy consumption area, mainly the area far away from the sink. The energy consumption of this area is much lower than that of the high energy consumption area. In this way, the GV-ACW MAC protocol has the following advantages:

(1) The energy utilization and network lifetime are improved. On the basis of the traditional protocol, the contention window size of the node is adjusted by adaptive method, and the residual energy of nodes far from the sink is used to appropriately increase the contention window size. This adaptive adjustment can not only reduce the energy consumption of the nodes in the near sink area, but also make full use of the energy of the nodes at the edge, so the network lifetime is improved.

(2) The network delay and packet loss rate are reduced. The network delay refers to the total time spent from the data preparation for submission to the sink node receiving the data. There are multiple sensor nodes in the WSN, so the average delay is used as the result indicator. In the protocol designed above, by adjusting the contention window size, the probability that two nodes choose the same backoff time is reduced. As a result, the delay and collision of the nodes in the network are lower, and the packet loss rate of the nodes is decreased accordingly.

(3) It improves the network throughput. In a WSN with the event occurrence probability of ω, the number of data packet transmissions is basically unchanged. The protocol in this paper reduces the possibility of node collision, and to a certain extent, improves the network throughput and communication performance.

2) OVERVIEW OF GV-ACW MAC PROTOCOL ALGORITHM

An adaptive adjustment contention window protocol is proposed, which has two main improvements: it can not only estimate the network performance of the network, but also automatically adjust the window size according to the contention condition of surrounding nodes. In the protocol, the network is mainly divided into a high energy consumption area (ℵ area) and a low energy consumption area (area). The protocol process consists of the following steps:

(1) Division of the area: According to the energy consumption of the network and based on Theorem 1, the system divides the network into two areas: the area within one hop to the sink called high energy consumption area and the rest area called low energy consumption area.

(2) Node hop count: First, all node hop values are initialized to 0. Then the sink node broadcasts a message. If one node receives the message, its hop value is recorded as H_i, which equals to the hop value of the sink plus 1. At the same time, it is marked as a visited node. Then, select the visited nodes in turn to broadcast messages like the sink node, and update the minimum hop value of other unvisited nodes.

(3) The shortest routing path to the sink node: if the next node is allowed to receive message and the nearest to the sink node, then it will be used as a relay to pass the message to the sink node.

(4) Adaptive adjustment process of the contention window: First, calculate the number of contentions of surrounding nodes and the number of hops of the node, and then the initial contention window value of the node is obtained through Eq. 11. Then, a time slot in the window is randomly selected by the node to send messages. If the message conflicts, the contention window parameters should be reduced to increase the size of the window to avoid possible conflicts next time. If there is no conflict, we are supposed to observe whether the delay threshold is exceeded, and if it is, continue reducing the contention window parameters appropriately to reduce the network delay. Until there is no conflict and the delay is less than the threshold, the adjustment process ends.

In the 802.11 protocol, according to the analysis in [45], there is a strong relationship between the contention window and network performance. When the network is congested, appropriately increasing the contention window can not only improve network throughput, but also reduce data conflicts and network latency. However, when the network is idle, the excessive contention window value will harm the throughput of the network instead, which in turn affects the performance of the network. Therefore, an appropriate mechanism to adjust the contention window is very important for the network. [46] shows that the size of contention window should dynamically change with the network conditions. When there are fewer contention nodes in an area, appropriately reducing the contention window size is conducive to improving network throughput. As mentioned above, the contention window determines some performance of the network, such as network delay, packet loss rate and so on. The calculation formula of the contention window of each node can be expressed as Eq. 11.

$$CW_i = CW_{init} * \left({}^{N_i}/_{H_i}\right). \qquad (11)$$

In the above formula, CW_i represents the contention window size of the node i, and CW_{init} represents the initial value of the contention window size, which can be calculated as $CW_{init}{=}(CW_{min} + CW_{max})/2$. N_i is the number of nodes contending around the node i, that is, the total number of nodes within the sensing radius of the node i, H_i represents the hop number of node i. The algorithm process is illustrated in step (2).

When the network structure changes, the size of the contention window in the above formula cannot be changed dynamically bringing a certain impact on the network, which is a key problem to be solved. The size of the contention window is directly proportional to the amount of data and inversely proportional to the data transmission rate. In order to reflect the actual situation of the contention window size more accurately, these two factors must be considered, and an adaptive parameter is added to achieve the adaptive adjustment, as shown in Eq. 12.

$$\begin{cases} CW_{adapt} = CW_{init} \times \frac{N_i}{H_i}\left(\frac{S_p}{v}\right)\left(\frac{1}{\alpha}\right) i \in \aleph \\ CW_{adapt} = CW_{init} \times \frac{N_i}{H_i}\left(\frac{S_p}{v}\right)\left(\frac{1}{\beta}\right) i \in \end{cases} \qquad (12)$$

And because $S_p = (z+1) + \frac{Z(1+Z)r}{2x}$, where $z = \left\lfloor \frac{R-x}{r} \right\rfloor$,x represents the distance of the node from the Sink node. In summary, Eq. 13 is available and as shown below.

$$\begin{cases} CW_{adapt} = CW_{init} \times \frac{N_i}{H_i}\frac{\left((z+1)+\frac{Z(1+Z)r}{2x}\right)}{v}\frac{1}{\alpha} \\ CW_{adapt} = CW_{init} \times \frac{N_i}{H_i}\frac{\left((z+1)+\frac{Z(1+Z)r}{2x}\right)}{v}\frac{1}{\beta} \end{cases} \qquad (13)$$

In Eq. 13, S_p denotes the size of the data packet, and v denotes the rate of data transmission. In addition, α and β are the coefficients of contention window in $\aleph$ area and area respectively. From the above formula, if α and β become smaller, the contention window size will become larger, and the network conflict and data packet loss rate will be reduced. Otherwise, the smaller contention window size will increase the network conflict and data loss packet rate.

Fig. 5 shows the relationship between the adaptive contention window size and the distance of nodes from the sink. The initial value of parameters is set as $\alpha = 0.5$, $\beta = 0.5$, and other parameters are shown in Table 2. It can be seen from

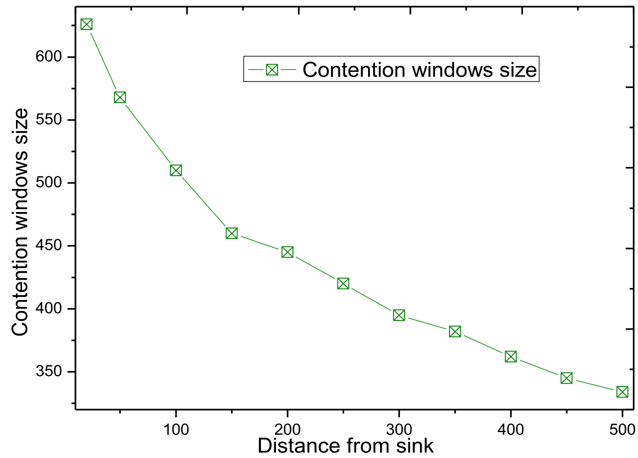

FIGURE 5. Relationship between contention window and distance.

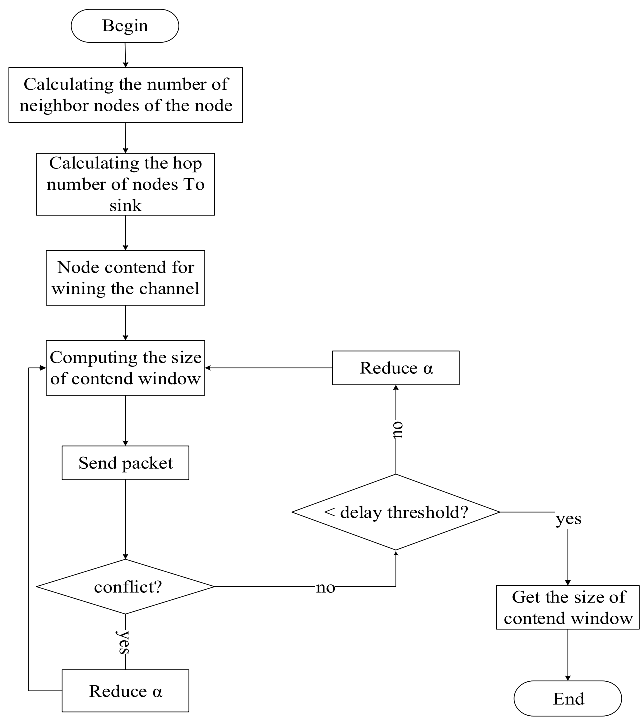

FIGURE 6. Flow chart of adjusting contention window in GV-ACW MAC protocol.

the Fig. 5 that the contention window size decreases with the increase of distance. The main reason is that: (1) the number of data packets is inversely proportional to the distance, so when the distance from the sink is larger, the number of packets is smaller; (2) the node hop count is proportional to the distance, so the larger distance can bring a larger hop count; (3) the number of contending nodes is proportional to the distance, so there is more contending nodes in the near sink area.

Combining the above formula and step 4, the process of the whole contention window adjustment algorithm is shown in Fig. 6.

TABLE 3. Abbreviations and their meanings.

Parameter (unit)	Value
v(Kbit/s)	200
CW_{init}	524
$DIFS$ (μs)	50
$\tau(slot\ Time)$(μs)	20
l_0(bit)	64
L(bit)	128
r(m)	50
t_s(ms)	250
t_a(ms)	100
α	Calculation-related
c	Calculation-related

3) DETERMINATION OF PARAMETERS IN GV-ACW MAC PROTOCOL

In this paper, the parameters of protocol algorithm are set in reference [51], [52]. The specific parameter values are shown in the table 1 and is as shown below.

V. THE PERFORMANCE ANALYSIS IN THEORY

This section gives the theoretical analysis and optimization of the GV-ACW MAC protocol through a series of theorems and inferences from several performance indicators such as energy consumption, network lifetime, network delay and packet loss rate.

A. ANALYSIS OF NODE ENERGY CONSUMPTION IN GV-ACW MAC PROTOCOL

In WSNs, the factors affecting the performance of packet transmission mainly include the amount of data that nodes need to forward and the congestion of network. The communication mechanism adopted in the model is RTS/CTS/DATA/ACK. Considering the length of RTS/CTS frame, the data packet is composed of the header, the effective section and the tail, which total length is L. The length of ACK packet is recorded as L_{ack}. If the speed of sending data in the network is v, the energy consumption for a node to complete a data transmission is as described in Theorem 2.

It has been proved in [10] that the number of data packets at a distance of x to the sink is:

$$S_x' = (z+1) + \frac{Z(1+Z)r}{2x}, \text{ where } z = \left\lfloor \frac{R-x}{r} \right\rfloor. \quad (14)$$

The probability that a node generates a data packet in a cycle is ω, and the number of data packets at a distance of x to the sink is:

$$S_x = S_x'\omega = ((z+1) + \frac{Z(1+Z)r}{2x})\omega, \text{ where } z = \left\lfloor \frac{R-x}{r} \right\rfloor. \quad (15)$$

Theorem 2: Assume the radius of the network is R, and the length of the contention window is L_{cw}. In one cycle, the active time is t_a, and the sleep time is t_s, and then the energy consumption of the node at distance of x is:

$$E_x = \varepsilon_s t_s' + \varepsilon_r t_r + \frac{L_{cw}+1}{2}\tau\varepsilon_{cw} + \varepsilon_s' t_s + \left(t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'\right)\varepsilon_{lpl}. \quad (16)$$

where $t_s' = \frac{S_x^s}{v}(L+L_{ack})$, $t_r = \frac{S_x^r}{v}(L+L_{ack})$.

Proof: Assuming that the distance between the node and the sink node is x, according to the lemma, the number of data packets sent and received is S_x^s and S_x^r, respectively. Then:

The reception time of the node is:

$$t_r = \frac{S_x^r L}{v} + \frac{S_x^r L_{ack}}{v} = \frac{S_x^s}{v}(L+L_{ack}). \quad (17)$$

The sending time of the node is:

$$t_s' = \frac{S_x^s L}{v} + \frac{S_x^s L_{ack}}{v} = \frac{S_x^r}{v}(L+L_{ack}). \quad (18)$$

When contending for the channel, the node is in the active state, and the expectation of the transmission time slot selected from the contention window whose size is L_{cw} is:

$$E(L_{cw}) = \frac{1}{L_{cw}}(1+\cdots+L_{cw}) = \frac{1+L_{cw}}{2}. \quad (19)$$

And because the length of the time slot is τ, the total average back-off time spent is:

$$t_{cw} = \frac{1+L_{cw}}{2}\tau. \quad (20)$$

The low energy consumption time of the node is:

$$t_{lpl} = t_a - \frac{L_{cw}+1}{2}\tau\varepsilon_{cw} - t_r - t_s'. \quad (21)$$

According to the sleeping time of t_s, the total energy consumed by the node in one cycle is:

$$E_x = \varepsilon_s t_s' + \varepsilon_r t_r + \frac{L_{cw}+1}{2}\tau\varepsilon_{cw} + \varepsilon_s' t_s + \left(t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'\right)\varepsilon_{lpl}.$$

■

Theorem 2 above assumes that the success rate of sending packets is 100%. Obviously, it does not conform to the actual situation of the network, so the energy consumption situation without the above assumption for network transmission is given below. When the data packet is sent unsuccessfully, the data retransmission mechanism is used to ensure that the data packet transmission reaches certain reliability. The number of data packet retransmission is defined as c, and there is also a packet loss rate during the message sending process, defined as φ. Then the energy consumption of the node is as described in Theorem 3.

Theorem 3: Suppose the radius of the network is R, and the length of the contention window of the node is L_{cw}. The average backoff time selected by the node is $(L_{cw}+1)\tau/2$. In a cycle, the active time is t_a, and the sleep time is t_s. Then the energy consumption of the node at distance x is:

$$E_x^c = \varepsilon_s t_s^c + \varepsilon_r t_r^c + \frac{c\,(L_{cw}+1)}{2}\tau\varepsilon_{cw} + \varepsilon_s' t_s + \left(t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'\right)\varepsilon_{lpl}. \quad (22)$$

where $t_s^c = \frac{S_x^s}{v}\left(cL + \frac{L_{ack}}{1-\varphi}\right)$, $t_r^c = \frac{cS_x^r}{v}\left(L\varphi + \frac{L_{ack}}{1-\varphi}\right)$.

Proof: The average number of data packet retransmissions of the node is c, and the communication mechanism adopted by the model network is RTS/CTS/DATA/ACK. Therefore, after the node connecting to another node through the handshake, as long as the ACK is received when the data has been sent, it means the transmission completes. Messages may be lost during the transmission process, and the probability of loss is set to φ, so the probability of successfully receiving the message is $1-\varphi$. To successfully receive an ACK, the expected times of sending data is $1\big/(1-\varphi)$.

Suppose the distance between the node and the sink is x. According to the lemma, the number of data packets sent and received is S_x^s and S_x^r, respectively. Then the time it takes for the node to send data is:

$$t_s^c = \frac{S_x^s cL}{v} + \frac{S_x^s L_{ack}}{v(1-\varphi)} = \frac{S_x^s}{v}\left(cL + \frac{L_{ack}}{1-\varphi}\right). \quad (23)$$

In the process of receiving data, due to the packet loss rate and retransmissions, the number of data packets received by the node is actually $\varphi c S_x^r$. Because the ACK response is required for all received data packets, and the number of ACK response is $\frac{c}{1-\varphi}$, so the amount of ACK is $\frac{c}{1-\varphi}S_x^r$. Then the time it takes for the node to receive data is:

$$t_r^c = \frac{\varphi c S_x^r L}{v} + \frac{c}{1-\varphi}\frac{S_x^r L_{ack}}{v} = \frac{cS_x^r}{v}\left(L\varphi + \frac{L_{ack}}{1-\varphi}\right). \quad (24)$$

It can be obtained that the time when the node is in low power state is:

$$t_{lpl} = t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'. \quad (25)$$

Since the data packets need to be retransmitted c times, the average back-off time of the node is $\frac{c(L_{cw}+1)}{2}\tau$, where the sleeping time of the node is still t_s, so the total energy (i.e. E_x^c) consumed by the node in one cycle is:

$$\begin{aligned} E_x^c &= \varepsilon_s \frac{S_x^s}{v}\left(cL + \frac{L_{ack}}{1-\varphi}\right) + \varepsilon_r \frac{cS_x^r}{v}\left(L\varphi + \frac{L_{ack}}{1-\varphi}\right) \\ &\quad + \frac{c\,(L_{cw}+1)}{2}\varepsilon_{cw} + \varepsilon_s' t_s \\ &\quad + \left(t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'\right)\varepsilon_{lpl} \\ &= \varepsilon_s t_s^c + \varepsilon_r t_r^c + \frac{c\,(L_{cw}+1)}{2}\tau\varepsilon_{cw} + \varepsilon_s' t_s \\ &\quad + \left(t_a - \frac{L_{cw}+1}{2}\tau - t_r - t_s'\right)\varepsilon_{lpl}. \end{aligned}$$

■

Theorem 4: Assume the size of the contention window of the major node is L_{cw}, and the average size of the window of its contention nodes is $\overline{L}$. In a round, the relationship between the number of data retransmissions $c_{L_{cw}}$ and the contention window size is:

$$c_{L_{cw}} = (L-1)\left(\left(\frac{1}{L_{cw}\overline{L}}\right)^2 - \frac{\left(\frac{1}{L_{cw}\overline{L}}\right)^3}{1-\frac{1}{L_{cw}\overline{L}}}\right)\left(\frac{L_{cw}\overline{L}-1}{L_{cw}\overline{L}}\right). \quad (26)$$

Proof: Assuming that the random backoff time selected by the current node A is the same as the backoff time selected by the surrounding neighbor node B, the data sent will conflict, and then the data should be retransmitted. Because the contention window size of node A is L_{cw}, the probability of choosing to retransmit the data is:

$$P_A = \frac{1}{L_{cw}}. \quad (27)$$

The probability that node B will select this moment is:

$$P_B = \frac{1}{\overline{L}}. \quad (28)$$

Then, the one retransmitting scenario is that, node B chooses the same time slot as node A to send the first time, and in the second retransmission, node A and node B choose different time to send data to avoid conflicts, so the probability is:

$$P_1 = \frac{1}{L_{cw}} \times \frac{1}{\overline{L}} \times \frac{1}{L_{cw}}\left(1 - \frac{1}{\overline{L}}\right). \quad (29)$$

Similarly, we can deduce the following probability of j retransmissions:

$$P_j = (\frac{1}{L_{cw}})^{j+1} \times (\frac{1}{\overline{L}})^j \times \left(1 - \frac{1}{\overline{L}}\right). \quad (30)$$

Therefore, the number of retransmissions $EE(c)$ is:

$$\begin{aligned} c_{L_{cw}} &= P_1 \times 1 + P_2 \times 2 + \cdots + P_n \times nn \\ &= (L-1)\left\{\left(\frac{1}{L_{cw}\overline{L}}\right)^2 - \frac{\left(\frac{1}{L_{cw}\overline{L}}\right)^3 - \left(\frac{1}{L_{cw}\overline{L}}\right)^{n+2}\frac{1}{L_{cw}\overline{L}}}{1-\frac{1}{L_{cw}\overline{L}}} \right. \\ &\quad \left. - \left(\frac{1}{L_{cw}\overline{L}}\right)^{n+3} n\right\} \\ &\quad \times \left(\frac{L_{cw}\overline{L}-1}{L_{cw}\overline{L}}\right). \end{aligned} \quad (31)$$

Thus, we get:

$$c_{L_{cw}} = (L-1)\left(\left(\frac{1}{L_{cw}\overline{L}}\right)^2 - \frac{\left(\frac{1}{L_{cw}\overline{L}}\right)^3}{1-\frac{1}{L_{cw}\overline{L}}}\right)\left(\frac{L_{cw}\overline{L}-1}{L_{cw}\overline{L}}\right).$$

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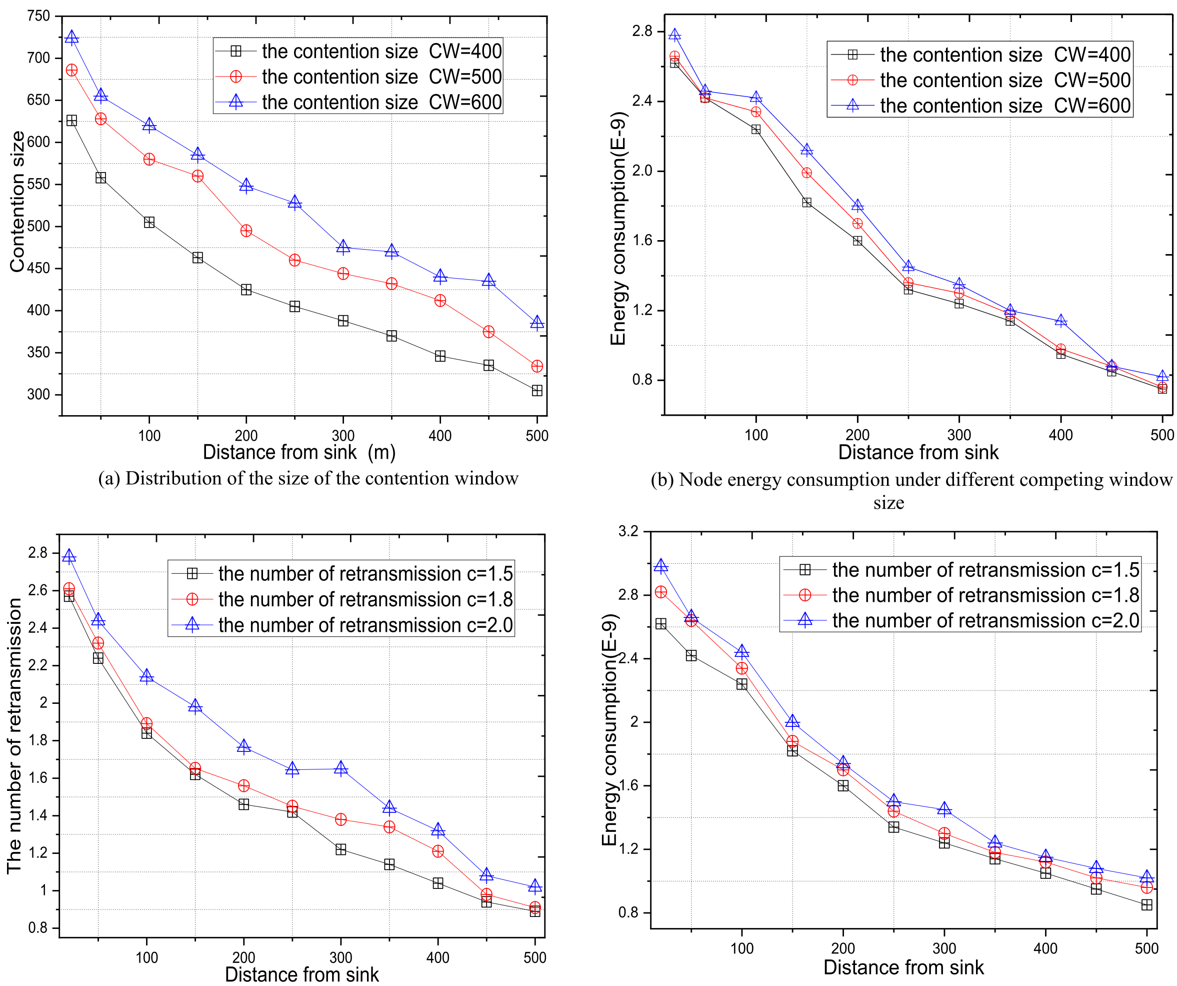


(a) Distribution of the size of the contention window

(b) Node energy consumption under different competing window size

(c) Distribution of data retransmission times at different distances

(d) Relationship of data retransmission times and energy consumption of nodes

FIGURE 7. The impact of contention window size on the retransmission times and energy consumption. (a) Distribution of the size of the contention window. (b) Node energy consumption under different competing window size. (c) Distribution of data retransmission times at different distances. (d) Relationship of data retransmission times and energy consumption of nodes.

From the above formulas, the results shown in Fig. 7 below can be obtained. Fig. 7(a) shows the size of the contention window of nodes at different distances. Fig. 7(b) illustrates the relationship between the energy consumption and the average contention window size. It can be seen from Fig. 7(a) and Fig. 7(b) that the larger the contention window size value, the more energy consumption. Fig. 7(c) shows the data retransmission times of nodes at different positions, and Fig. 7(d) illustrates the relationship between the retransmission times and the energy consumption. In these two figures, more retransmissions bring the greater energy consumption.

B. ANALYSIS OF AVERAGE TRANSMISSION DELAY IN GV-ACW MAC PROTOCOL

Network delay is a critical indicator in the network performance. In this paper, it is defined as the time spent from the node preparing to send data to the sink node receiving the data. It mainly consists of the sending time, waiting time, and propagation time. The delay is closely related to the packet size, the contention window size, and the number of surrounding contending nodes. When the number of contending nodes around is smaller, the network performance is better and the delay is shorter. When the data transmission rate is fixed, the larger node data packets make the transmission time longer. And when the contention window size is appropriately larger, the conflicts will be reduced and the waiting delay will be shorter. From the above analysis, it can be concluded that there is a functional relationship between the delay and these three factors, which is recorded as follows:

$$T_{delay} = F\left(S, CW_{n_i}, Num\right). \tag{32}$$

In the above formula, S represents the amount of data sent by the node, and CW_{n_i} is the contention window size of the n_i node, and Num represents the number of surrounding contending nodes, which is directly proportional to factors such as the node density ω, so the function can also be recorded as:

$$T_{delay} = F\left(S, CW_{n_i}, \omega\right). \tag{33}$$

Theorem 5: The network delay function is $T_{delay} = F(S, CW_{n_i}, \omega)$, then when the distance from the sink node is x, the entire network delay is:

$$\begin{aligned} T^x_{delay} &= F\left(S_x, CW^x_{n_i}, \omega\right) \\ &= \left(\frac{S_x * L}{v} + \frac{x}{v} + \frac{\partial}{CW^x_{n_i}}\right) * \left(\frac{1}{1-\varphi}\right). \end{aligned} \tag{34}$$

Proof: (i) The data transmission rate in the network is v, and S_x data packets need to be sent at the distance of x from the sink. Then the total length of the data packet is $S_x * L$, and the entire transmission delay is $\frac{S_x * L}{v}$. (ii) The contention window size of the node is $CW^x_{n_i}$. Because the contention window size is inversely proportional to the delay, so the waiting delay of the node when selecting the data transmission slot is $\frac{\partial}{CW^x_{n_i}}$, where ∂ is a window coefficient. (iii) The transmission distance is x, so the transmission time is $\frac{x}{v}$. (iv) The packet loss rate during data transmission is φ, so the probability of the node successfully sending a message is $1 - \varphi$. Then it is expected to send $\frac{1}{1-\varphi}$ times to ensure successful reception. Therefore, it can be concluded as:

$$T^x_{delay} = \left(\frac{S_x * L}{v} + \frac{x}{v} + \frac{\partial}{CW^x_{n_i}}\right) * \left(\frac{1}{1-\varphi}\right).$$

■

The average contention window size of the nodes in the high energy consumption area under the GV-ACW MAC protocol is 10.894% and 8.1001% greater than that under S-MAC and T-MAC respectively. And because the delay $T^x_{delay} = F(S_x, CW^x_{n_i}, \omega)$ is inversely proportional to the CW size, the larger the CW makes the network delay smaller. For the GV-ACW MAC, S-MAC and T-MAC protocols, there are the relationship: $\overline{CW}_{cwa} > \overline{CW}_{smac}, \overline{CW}_{cwa} > \overline{CW}_{tmac}$. Therefore, the node at distance x from the sink node has the following relationship:

$$\begin{cases} T^x_{cwa\_delay} = F\left(S_x, \overline{CW}_{cwa}, \omega\right) < T^x_{smac\_delay} \\ \qquad = F\left(S_x, \overline{CW}_{smac}, \omega\right) \\ T^x_{cwa\_delay} = F\left(S_x, \overline{CW}_{cwa}, \omega\right) < T^x_{tmac\_delay} \\ \qquad = F\left(S_x, \overline{CW}_{tmac}, \omega\right). \end{cases} \tag{35}$$

Theorem 6: On the basis of the previous work, suppose that the transmitting radius of each hop in the GV-ACW MAC protocol node is r. So the total delay of sending messages for the node at the distance x from the sink to is:

$$T^x_{all\_delay} = \sum_{i=0}^{\lceil \frac{x}{r} \rceil} F(S_{ir}, CW^{ir}_{n_i}, \omega). \tag{36}$$

Proof: In this model network, the messages reach the sink after multi-hop transmission. In the process of sending messages, conflict may occur at each segment of the route and cause the delay, so the whole route can be regarded as the multiple combinations of Theorem 5, that is, the node at the distance x from the sink first sends information to the node distant $x - r$ from the sink, then $x - 2r$, $x - 3r$...and so on, until the message is sent to the destination, so the total delay is:

$$\begin{aligned} T^x_{all\_delay} &= F\left(S_{x-r}, CW^{x-r}_{n_i}, \omega\right) + F\left(S_{x-2r}, CW^{x-2r}_{n_i}, \omega\right) \\ &\quad + \cdots + F\left(S_{x\%r}, CW^{x\%r}_{n_i}, \omega\right). \end{aligned}$$

$$T^x_{all\_delay} = \sum_{i=0}^{\lceil \frac{x}{r} \rceil} F(S_{ir}, CW^{ir}_{n_i}, \omega).$$

■

Theorem 7: In the GV-ACW MAC protocol, the total delay T_{cwa_total} and the average delay T_{cwa_avg} of network are described by the following formula:

$$\begin{cases} T_{cwa\_total} = \int_0^R \int_0^{2\pi} T^x_{all\_delay} x\omega dx d\theta \\ T_{cwa\_avg} = \int_0^R \int_0^{2\pi} T^x_{all\_delay} x dx d\theta / (\pi R^2). \end{cases} \tag{37}$$

Proof: The nodes are evenly distributed in the network model. For any sector area with the angle $d\theta$ and the diameter dx in the network, when $d\theta$ and dx are small enough, the area can be regarded as a rectangle. Therefore, the number of nodes in the small area is $x\omega dx d\theta$. According to Theorem 6, the delay to reach the sink node in this area is $T^x_{all\_delay} x\omega dx d\theta$, so the delay of the entire network is as follows:

$$T_{cwa\_total} = \int_0^R \int_0^{2\pi} T^x_{all\_delay} x\omega dx d\theta.$$

The average delay of the network is:

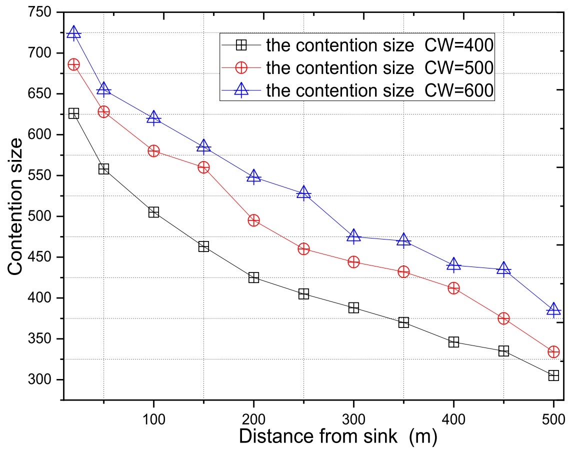
$$\begin{aligned} T_{cwa\_avg} &= \int_0^R \int_0^{2\pi} T^x_{all\_delay} x\omega dx d\theta / \left(\pi R^2 \omega\right) \\ &= \int_0^R \int_0^{2\pi} T^x_{all\_delay} x dx d\theta / \left(\pi R^2\right). \end{aligned}$$

■

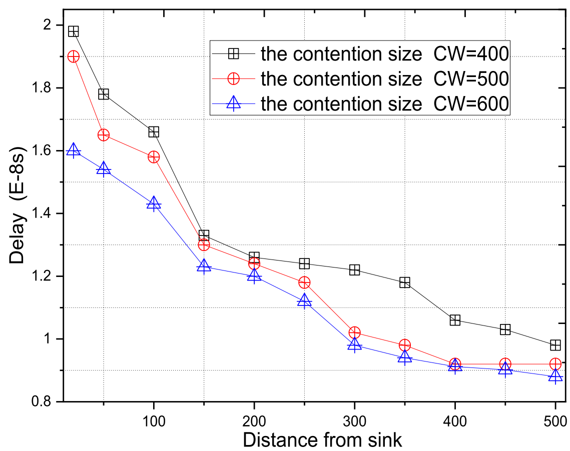
According to the above formula, Fig. 8 is obtained, which represents the average delay of nodes applying different contention window sizes. It can be seen from Fig. 8 that the average delay decreases with the distance of nodes from the sink, and the larger contention window size leads to a smaller average delay.

C. ANALYSIS OF DATA PACKETS TRANSMISSION SUCCESS RATE IN GV-ACW MAC PROTOCOL

The success rate of data packet transmission is actually also a very important performance indicator, similar to the network delay. The success rate is closely related to the following factors: (i) The number of data packets. More data packets sent put greater pressure on the network, which makes more packets are lost during the transmission and the success rate is lower. (ii) The size of the contention window. When the contention window is larger, the probability of data collision is smaller, which affects the network less, so the data



(a) Distribution of contention window size



(b) Relationship between the average delay of nodes under different contention window size

FIGURE 8. The impact of contention window size on the transmission delay. (a) Distribution of contention window size. (b) Relationship between the average delay of nodes under different contention window size.

transmission success rate is higher. (iii) The number of surrounding contending nodes. Similar to the previous factors, more contending nodes keep up the pressure on the network channel and decrease the success rate of data transmission. From the above analysis, it can be concluded that there is a functional relationship between the success rate and the above factors:

$$P_{success} = C\left(S, CW_{n_i}, Num\right). \tag{38}$$

In the formula, S represents the amount of data sent by the node, and CW_{n_i} represents the value of the contention window size of the n_i node. Because the number of surrounding contending nodes is related to the node density ω, the above formula can be changed to:

$$P_{success} = C\left(S, CW_{n_i}, \omega\right). \tag{39}$$

Inference 1: The function of data transmission success rate is $P_{success} = C(S, CW_{n_i}, \omega)$, and then the data transmission success rate of nodes distant x from the sink is:

$$P^x_{success} = C\left(S_x, CW^x_{n_i}, \omega\right). \tag{40}$$

Proof: Suppose the number of data packets sent by the node x away from the sink is S_x, and the contention window size of the node is $CW^x_{n_i}$, so the transmission success rate can be expressed:

$$P^x_{success} = C\left(S_x, CW^x_{n_i}, \omega\right).$$

■

In the GV-ACW MAC protocol, an adaptive contention window is used. Considering the problem of energy surplus, the average contention window designed for the nodes far from the sink is larger than that in the S-MAC and T-MAC protocols. From $P^x_{success}$, the network transmission success rate is directly proportional to the size of the contention window. The larger contention window size brings a higher data transmission success rate. Therefore, for the node distant x from the sink, there is the following relationship:

$$\begin{cases} P^x_{cwa\_success} = C\left(S_x, \overline{CW}_{cwa}, \omega\right) > P^x_{smac\_success} \\ \qquad = C\left(S_x, \overline{CW}_{smac}, \omega\right) \\ P^x_{cwa\_success} = C\left(S_x, \overline{CW}_{cwa}, \omega\right) > P^x_{tmac\_success} \\ \qquad = C\left(S_x, \overline{CW}_{tmac}, \omega\right). \end{cases} \tag{41}$$

Inference 2: In the GV-ACW MAC protocol, suppose that the transmitting radius of each hop in the GV-ACW MAC protocol node is r and the transmission success rate function is $P_{success} = C(S, CW_{n_i}, \omega)$. Then the transmission success rate of the node distant x from the sink is:

$$P^x_{all\_delay} = \prod_{i=0}^{\lceil \frac{x}{r} \rceil} F\left(S_{ir}, CW^{ir}_{n_i}, \omega\right). \tag{42}$$

Proof: Similar to Theorem 6, because conflict may occur at each segment of the route, so the whole route can be regarded as the multiple combinations of Inference 1, that is, the node at the distance x from the sink first sends information to the node distant $x - r$ from the sink, then $x - 2r$, $x - 3r$...and so on, until the message is sent to the destination. The current success rate of data transmission is the product of previous success rate. Therefore, when the data reaches sink, the transmission success rate of the entire network is:

$$P^x_{all\_success} = C\left(S_{x-r}, CW^{x-r}_{n_i}, \omega\right) * C\left(S_{x-2r}, CW^{x-2r}_{n_i}, \omega\right) * \cdots * C\left(S_{x\%r}, CW^{x\%r}_{n_i}, \omega\right).$$

$$P^x_{all\_delay} = \prod_{i=0}^{\lceil \frac{x}{r} \rceil} F(S_{ir}, CW^{ir}_{n_i}, \omega).$$

■

Theorem 8: In the GV-ACW MAC protocol, the transmission success rate of the entire network P_{cwa_total} and the average transmission success rate P_{cwa_avg} are as follows:

$$\begin{cases} P_{cwa\_total} = \int_0^R \int_0^{2\pi} P^x_{all\_success} x\omega dx d\theta \\ P_{cwa\_avg} = \int_0^R \int_0^{2\pi} P^x_{all\_success} x dx d\theta / (\pi R^2). \end{cases} \tag{43}$$

Proof: Similar to the proof of Theorem 7, any small sector area with angle $d\theta$ and diameter dx can be considered as a rectangle. Therefore, the total number of nodes in this area is $x\omega dxd\theta$. According to Inference 2, the transmission success rate of this area is $P^x_{all\_success}x\omega dxd\theta$, then the transmission success rate of the entire network can be expressed as: $P_{cwa\_total} = \int_0^R \int_0^{2\pi} P^x_{all\_success}x\omega dxd\theta$.

The average data transmission success rate is:

$$\begin{aligned} P_{cwa\_avg} &= \int_0^R \int_0^{2\pi} P^x_{all\_success}x\omega dxd\theta / \left(\pi R^2 \omega\right) \\ &= \int_0^R \int_0^{2\pi} P^x_{all\_success}xdxd\theta / \left(\pi R^2\right). \end{aligned}$$

■

D. ANALYSIS OF NETWORK LIFETIME UNDER GV-ACW MAC PROTOCOL

Improving the network lifetime is one of the main design goals of WSN and an important indicator to measure the network performance. The network lifetime under the GV-ACW MAC protocol is analyzed below.

Theorem 9: In the GV-ACW MAC protocol, the nodes close to the sink adopt an adaptively adjusted contention window, and the nodes far from the sink adopt a larger value than the adaptive contention window. Then the lifetime of the node at distance x from the sink is:

$$\tau_x = \frac{E}{E_x}. \tag{44}$$

where

$$\begin{aligned} E_x &= \varepsilon_s t_s^c + \varepsilon_r t_r^c * \varepsilon_{cw} + \varepsilon_s' t_s \\ &\quad + \left(t_a - \frac{L_{cw}+1}{2} * slot_{Time} - t_r - t_s'\right) * \varepsilon_{lpl}, \end{aligned}$$

and

$$t_s^c = \frac{S_x^s}{v}\left(cL + \frac{L_{ack}}{1-\varphi}\right), t_r^c = \frac{cS_x^r}{v}(L\varphi + \frac{L_{ack}}{1-\varphi}).$$

Proof: Assuming that the average size of the contention window in the network is L_{cw}, in the GV-ACW MAC protocol, Theorem 3 shows that at distance x from the sink node, the number of data retransmissions is c, and the packet loss rate is φ. The energy consumption of the node is:

$$\begin{aligned} E_x &= \varepsilon_s \frac{S_x^s}{v}\left(cL+\frac{L_{ack}}{1-\varphi}\right)+\varepsilon_r \frac{cS_x^r}{v}\left(L\varphi+\frac{L_{ack}}{1-\varphi}\right) \\ &\quad + \frac{c\left(L_{cw}+1\right)}{2}\varepsilon_{cw}+\varepsilon_s' t_s+\left(t_a-\frac{L_{cw}+1}{2}\tau-t_r-t_s'\right)\varepsilon_{lpl}. \end{aligned} \tag{45}$$

And because

$$t_s^c = \frac{S_x^s}{v}\left(cL + \frac{L_{ack}}{1-\varphi}\right), t_r^c = \frac{cS_x^r}{v}\left(L\varphi + \frac{L_{ack}}{1-\varphi}\right). \tag{46}$$

The initial energy of the node is E, and the energy consumption of each transmission is E_x, so the lifetime of nodes at the distance x from the sink can be expressed as:

$$\tau_x = \frac{E}{E_x}.$$

■

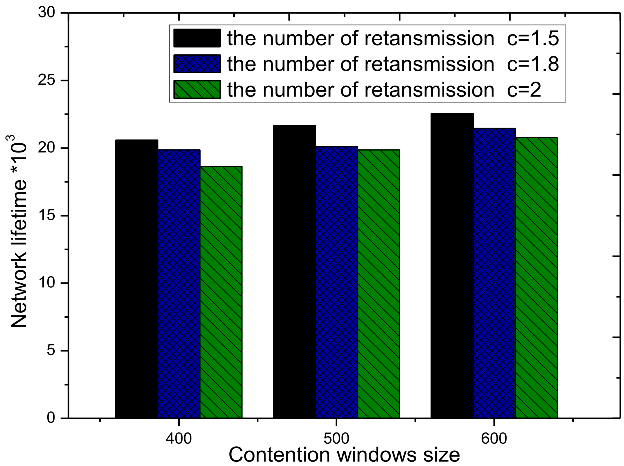


FIGURE 9. The relationship between the network lifetime under different contention window sizes.

Based on the above formulas, the energy consumption under different contention window sizes is shown in Fig. 9. From Fig. 9, it can be seen that the larger contention window size of the node makes longer network lifetime. In addition, applying the same contention window, the nodes with more retransmissions have shorter network lifetime.

Theorem 10: In the GV-ACW MAC protocol, the energy utilization of the network is:

$$\partial = \frac{\int_0^R \int_0^{2\pi} E_x \omega xdxd\theta}{\pi R^2 E\omega}. \tag{47}$$

Proof: In the GV-ACW MAC protocol, similar to Theorem 8, for any sector with angle $d\theta$ and the diameter dx, when $d\theta$ and dx approach to 0, the area can be regarded as a rectangle. Therefore, the total number of nodes in this area is $x\omega dxd\theta$, and the total initial energy is:

$$E_{x\_init} = E\omega xdxd\theta. \tag{48}$$

The initial energy of the entire network is:

$$E_{all} = \int_0^R \int_0^{2\pi} E\omega xdxd\theta = \pi R^2 E\omega. \tag{49}$$

The energy consumption of the entire network is:

$$E_{consume} = \int_0^R \int_0^{2\pi} E_x \omega xdxd\theta. \tag{50}$$

Therefore, the effective utilization rate of the network is:

$$\partial = \frac{E_{consume}}{E_{all}} = \frac{\int_0^R \int_0^{2\pi} E_x \omega xdxd\theta}{\pi R^2 E\omega}.$$

■

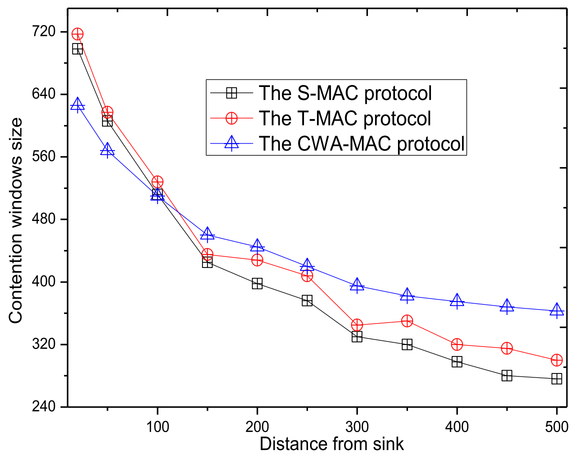


FIGURE 10. Experimental results of the distribution of competing window sizes.

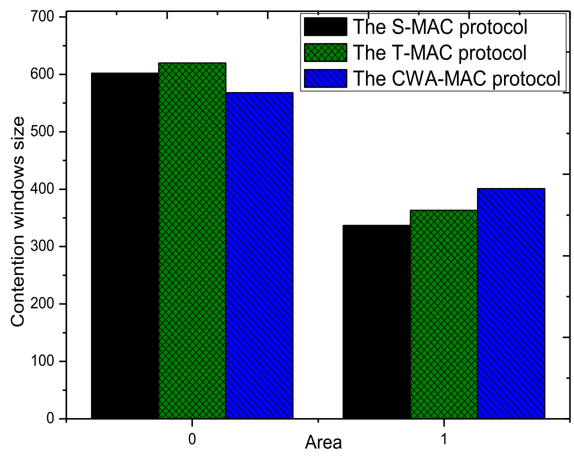


FIGURE 11. Regional distribution of average contention window size.

VI. EXPERIMETAL RESULTS AND ANALYSIS

OMNET++ is employed for experimental verification [59]. OMNET++ is an object-oriented network simulation platform integrating JAVA and C++. It provides users with a friendly interface and convenient development mode, which has been widely recognized [59]. In this article, the OMNET++ is applied to conduct experimental simulations and verify the theory and effectiveness of the GV-ACW MAC protocol. The analysis is mainly based on the following indicators: (1) Contention window size; (2) Energy consumption; (3) Average delay; (4) Data transmission success rate. In the experiment, to make the results more convincing and effective, the two typical MAC protocols in WSN, S-MAC and T-MAC, are compared with the protocol proposed.

In the experiments, the nodes adjust the size of the contention window according to an adaptive algorithm. The main parameters of the experimental network environment are set as follows: a circular network with a radius of $R = 500$, and the sink node is located at the center of the network. Moreover, 1000 or 700 sensor nodes, which represent different node densities, are randomly and uniformly distributed with the sensing radius $r = 50$.

A. EXPERIMENTAL RESULTS OF DIFFERENT CONTENTION WINDOW SIZES IN THE NETWORK

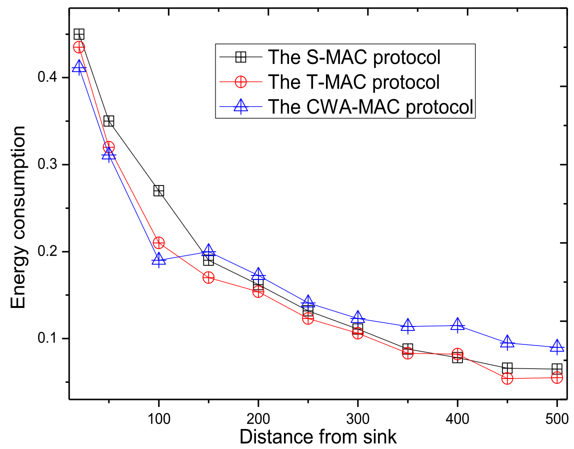
In this section, the GV-ACW MAC proposed in this article is compared with S-MAC and T-MAC to illustrate the theory and effectiveness of the GV-ACW MAC. Fig. 10 shows the contention window sizes of nodes with different distances from the sink in the three protocols. It can be seen that for the S-MAC protocol, the nodes solve the data conflictions by increasing the contention window size. There are many nodes close to the sink sending data, so the probability of data collision increases in the area. To avoid the data collision, the contention window size is adjusted larger. Compared with S-MAC, T-MAC shortens the active state time, causing more energy is saved. When data packets collide, the sleeping node will be activated, hence it has stronger adaptability.

In Fig. 10, the size of the contention window is only slightly larger than S-MAC. For the GV-ACW MAC protocol proposed in this paper, when more data is gathered by the node, the contention window will be adjusted adaptively according to the node density, the data amount and the area where the node is located. The adjustment of the GV-ACW MAC is more sensitive, instead of waiting for the backoff step by step. In addition, the contention window size is deliberately amplified in the far sink area to schedule the data transmission. Overall, it can be seen from the Fig. 10 that when the distance from sink is larger than 100, the size of the contention window of the GV-ACW MAC protocol is greater than that under the S-MAC and T-MAC protocols, while the contention window size of the GV-ACW MAC is smaller when the distance from sink is less than 10.

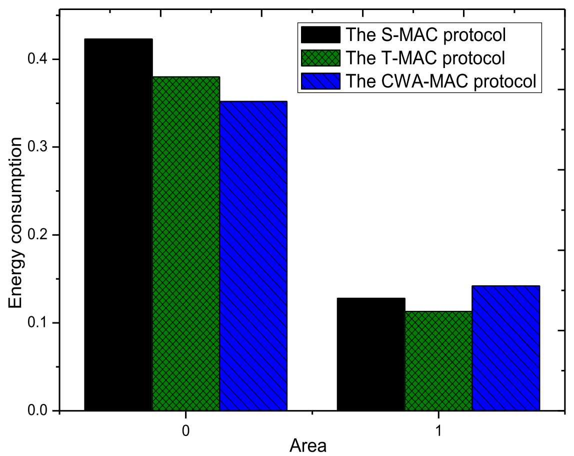
Fig. 11 shows the average contention window size in different areas, where 0 indicates the high energy consumption area, while 1 indicates the low energy consumption area. As can be seen from Fig. 11, in the same protocol, the average contention window of the high energy consumption area is larger than that of the low energy consumption area, which is consistent with the previous theoretical analysis. Because in the high energy consumption area, there are more data packets need to be transmitted, and the number of nodes in contention is large, so a greater contention window is required to better resolve conflicts. Secondly, in different protocols, the average contention window size in the high energy consumption area under the GV-ACW MAC is 0.9435 times that of S-MAC and 0.9161 times that of T-MAC. In the far sink area, the average contention window size of nodes under the GV-ACW MAC is 0.9435 times that of S-MAC and 0.9161 times that of T-MAC.

B. COMPARATIVE EXPERIMENTAL RESULTS OF ENERGY CONSUMPTION AND NETWORK LIFETIME

Fig. 12 illustrates the energy consumption of nodes under the three protocols. In the high energy consumption area of the same protocol, the energy consumption of the nodes



(a). Comparison experimental results of overall energy consumption



(b). Comparison experimental results of average energy consumption in different areas

FIGURE 12. Comparison experimental results of overall energy consumption and average energy consumption in different areas. (a). Comparison experimental results of overall energy consumption. (b). Comparison experimental results of average energy consumption in different areas.

closer to the sink is larger, due to more data packets undertaken by these nodes. Conversely, in the low energy consumption area, the farther the node is from the sink node, the slower the energy consumption. This is because nodes can send data packets through multiple paths, which share a large number of packets transmitting, so the energy consumption is more balanced in this area. In the high energy consumption area, the energy consumption under the GV-ACW MAC protocol is smaller than that of the S-MAC and T-MAC protocols. Combining with Fig. 10, we can see that in the high energy consumption area, the average contention window size of the GV-ACW MAC is smaller than that of S-MAC and T-MAC, because the nodes of the latter two need to maintain activities during the contention window period, so energy consumption of GV-ACW MAC is smaller than that of S-MAC and T-MAC. For T-MAC and S-MAC, although the competing window of T-MAC is larger than

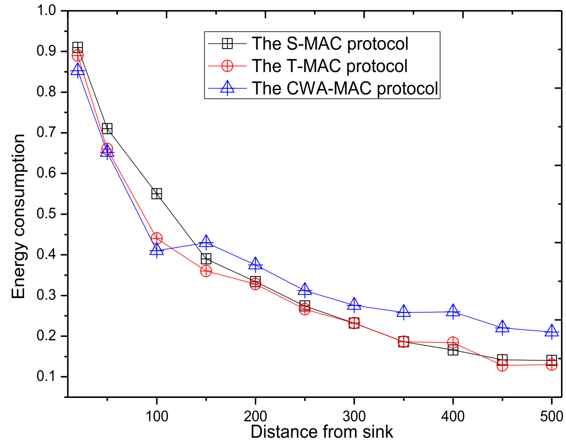


FIGURE 13. Comparison experimental results of energy utilization of the three protocols.

S-MAC in the high energy consumption zone, T-MAC uses a flexible alternating sleep and activity state mechanism, so T-MAC consumes less energy than S-MAC. The average contention window in the low energy consumption zone, GV-ACW MAC is greater than S-MAC and T-MAC, so the energy consumption of GV-ACW MAC is greater than the energy consumption of S-MAC and T-MAC. As in the high energy consumption area, the energy consumption of T-MAC is less than that of S-MAC. And by calculation, when the size of the contention window is adjusted to that shown in Fig. 10, a compromise is achieved. In the low energy consumption area, the average energy consumption of the GV-ACW MAC protocol is 1.2566 times that of the T-MAC protocol, and 1.1094 times of S-MAC protocol. In the high energy consumption area, the average energy consumption of the GV-ACW MAC protocol is 0.9263 times that of the T-MAC protocol and 0.8322 times that of the S-MAC protocol. Overall, the average energy consumption of the GV-ACW MAC protocol is 1.1905 times that of the T-MAC protocol and 1.0540 times that of the S-MAC protocol.

Fig. 13 shows the relationship between energy utilization rates under the three protocols. It can be seen from the Fig.13 that in the low energy consumption area, that is, the peripheral area, the energy utilization rate of the GV-ACW MAC is higher than that of the T-MAC and S-MAC protocols. The main reason is that GV-ACW MAC protocol makes reasonable use of the original "redundant" energy by increasing the contention window of the nodes, thus making better use of the effective resources.

Fig. 14 shows the relationship between the network lifetimes of the three protocols at different node densities. The network lifetime here refers to when a node in the wireless sensor network dies, then the network lifetime will end. From the experimental results, it can be seen that under different node densities, the network lifetime of a large node density is shorter than the network lifetime of a small node density. Because the node density is large, under the same event occurrence probability, the possibility of nodes seizing the

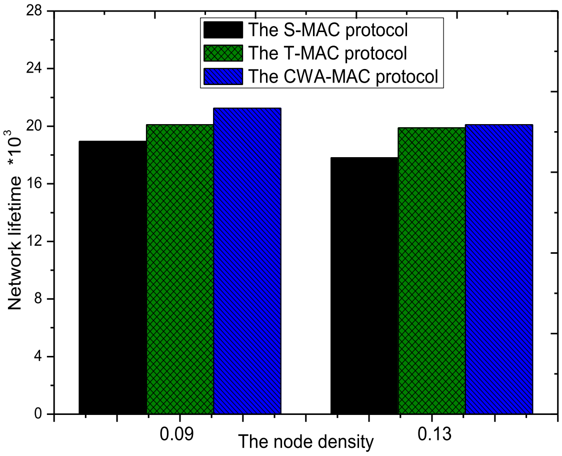


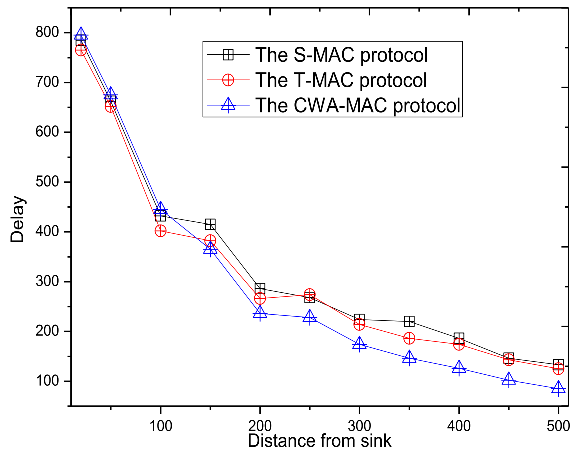
FIGURE 14. Comparison experiment results of network life at different node densities.

same channel increases, so there is the above conclusion. In the same node density, when the node density is 0.09, the network lifetime of the GV-ACW MAC protocol is 1.1214 times that of the S-MAC protocol, and 1.0571 times that of the T-MAC protocol. When the node density is 0.13, the network lifetime of the GV-ACW MAC protocol is 1.1285 times that of the S-MAC protocol, and 1.0512 times that of the T-MAC protocol.

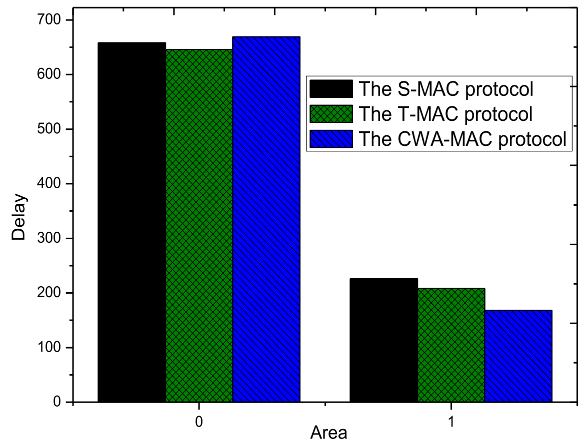
C. COMPARATIVE EXPERIMENTAL RESULTS OF AVERAGE DELAY

Fig. 15 shows the average delay of nodes under the three protocols. It can be seen from the Fig. 15 that in the high energy consumption area of the same protocol, the nodes closer to the sink have relatively larger transmission delay, which is due to the large number of contending nodes in this area and the huge amount of data packets undertaken by the node. However, in the low energy consumption area, the farther the node is from the sink node, the smaller the average delay. This is because the number of contending nodes in the area is small, and the node has multiple paths to share the data packet transmission, which evenly divide packet pressure of small packets. Moreover, it can be seen that the average delay change trends of the three protocols are similar. Especially when the data enters the area $2r$ away from the sink, the change of delay becomes relatively flat. From the previous analysis, the data amount on the second hop route is more than 4 times that of the outermost node. Therefore, the delay of the nodes in the area varies greatly.

Comparing the average delay under different protocols, it can be seen that in the high energy consumption area, the average delay of the T-MAC protocol is less than the S-MAC protocol. This is because the node in the T-MAC protocol can be stimulated and automatically activate and then transmit data information if it is in a sleep state. However, in the S-MAC protocol, the node alternates between sleep and active time, so the node must wait for it to wake up from sleep time to transmit data information. From the



(a). The overall average network delay under different protocols



(b). Average network delay in different energy consumption areas

FIGURE 15. The transmission delay under three protocols applying different contention window size. (a). The overall average network delay under different protocols. (b). Average network delay in different energy consumption areas.

previous Fig. 10, in the low energy consumption area, for the GV-ACW MAC protocol, the node in this area adopts a contention window size value greater than that obtained by adaptation, and its contention window is greater than that under the S-MAC and T-MAC protocols. According to the previous theoretical analysis, when the contention window is appropriately large, the collision between nodes is reduced, and the communication capability of the network is enhanced. Therefore, the average delay of the GV-ACW MAC is less than that of the T-MAC protocol.

According to experimental data, the average network delay of the GV-ACW MAC protocol in the low energy consumption area is 0.8077 times that of the T-MAC protocol and 0.7434 times that of the S-MAC protocol. However, in the high energy consumption area, the average network delay of the GV-ACW MAC protocol is 1.0356 times that of the T-MAC protocol and 1.0167 times that of the S-MAC protocol. Overall, the average network delay of the GV-ACW MAC protocol is 0.8533 times that of the T-MAC protocol and 0.7981 times that of the S-MAC protocol.

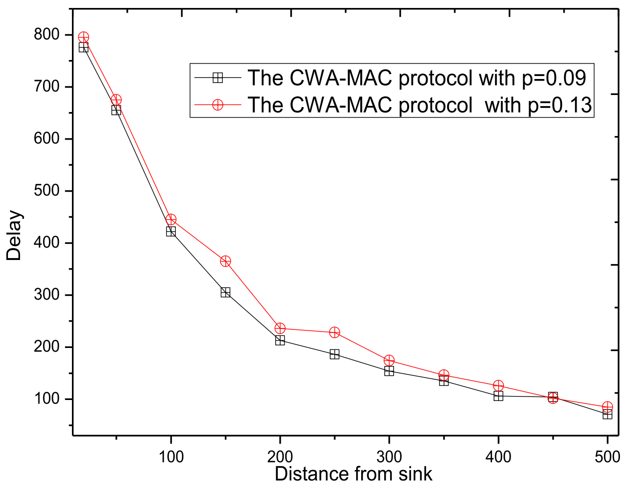


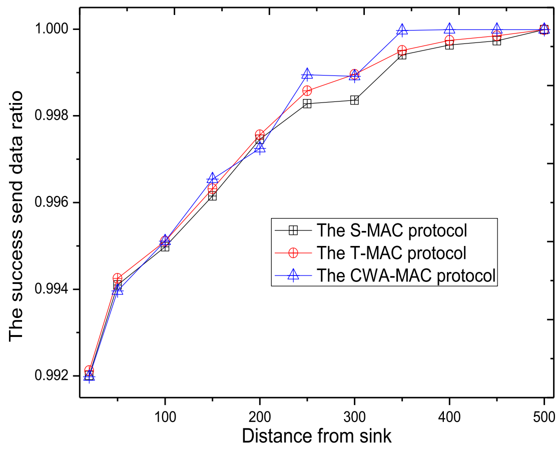
FIGURE 16. Network delay under different node densities.

Fig. 16 shows the average delay of the GV-ACW MAC protocol under different node densities. We can see that at the same distance from the sink node, the average delay of nodes increases with the node density, for there are more contending nodes in the dense area, so the probability of collisions will increase and the communication performance of the network becomes worse, resulting in increased delay. Because they are all evenly distributed, it can be seen from the Fig. 16 that the trends of the two curves are basically the same. The position at the distance of $2r$ from the sink node is a critical point. When it is greater than $2r$, the delay of nodes changes smoothly, otherwise it changes quickly.

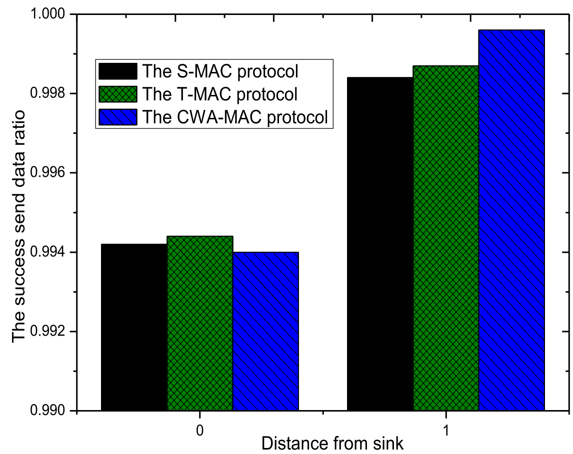
D. COMPARATIVE EXPERIMENTAL RESULTS OF DATA TRANSMISSION RATE

Fig. 17 shows the change of data transmission success rate with the distance from the sink under the three protocols. It can be seen from Fig. 17 that in the high energy consumption area of the same protocol, the closer the node is to the sink node, the lower the data transmission success rate. This is mainly due to the large number of nodes contending in this area and the large amount of data undertaken by the nodes. Conversely, in the low energy consumption area, the farther the node is from the sink node, the higher the success rate of data transmission. This is because the number of contending nodes in the area is small, and nodes have multiple paths to choose for data transmission, thereby the transmission pressure is shared evenly by more than one path.

By comparing different protocols, it can be seen that when the distance from the sink is the same, the success rate of data transmission under the T-MAC protocol is higher than that under the S-MAC protocol, for the T-MAC protocol adopts a mechanism for flexibly switching active state and sleeping state, while the S-MAC protocol uses a fixed rotation of these two states. Therefore, T-MAC will not cause data transmission failure due to the sleeping process. Combining Fig. 8 and the previous Inference 2, in the low energy consumption area, the average contention window size of nodes under the T-MAC protocol is greater than that under the S-MAC protocol, so the data transmission success rate of the T-MAC protocol is higher. Similarly, the data transmission success rate of the GV-ACW MAC protocol is greater than that of the T-MAC protocol. In the GV-ACW MAC protocol, the nodes in this area adopt a larger window size than that obtained by self-adaptation, which is larger than the S-MAC and T-MAC protocols. According to the previous theoretical analysis, the data transmission success rate under the GV-ACW MAC protocol is greater than that under the T-MAC protocol.



(a). The data transmission success rate of the entire network under different protocols



(b). Data transmission success rate in different areas

FIGURE 17. The data transmission success rate under three protocols applying different contention window size. (a). The data transmission success rate of the entire network under different protocols. (b). Data transmission success rate in different areas.

From the experimental results, the comparison of the data transmission success rate of the three protocols can be obtained. In the high energy consumption area, the data transmission success rate under the GV-ACW MAC protocol is 1.103 and 1.143 times that of the T-MAC protocol and the S-MAC protocol respectively. However, in the low energy consumption area, the data transmission success rate under the GV-ACW MAC protocol is 0.995 and 0.996 times that of the T-MAC protocol and the S-MAC protocol respectively. Overall, the data transmission success rate of the GV-ACW

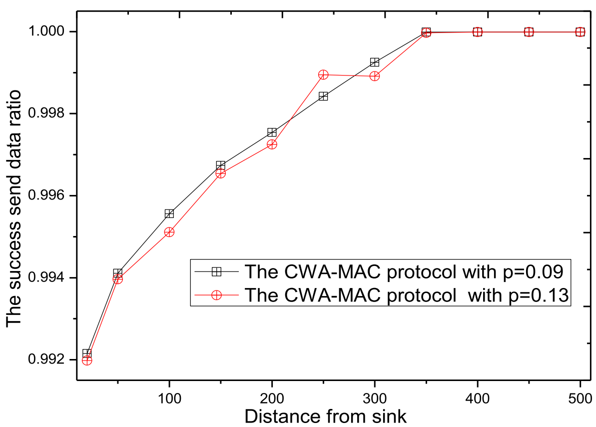


FIGURE 18. **Data transmission success rate of different node densities.**

MAC protocol is 1.0814 and 1.1136 times that of the T-MAC protocol and the S-MAC protocol on average.

Fig. 18 shows the success rate of GV-ACW MAC protocol data transmission under different node density conditions. From the diagram, it can be seen that a higher density of nodes leads to the lower data transmission success rate, because more nodes contend at the same time and the possibility of conflict increases. When the density of nodes is small, the possibility of node collisions is small, so the possibility that nodes need to retransmit data is reduced. In this network, the nodes are evenly distributed, so it can be seen that the curve trends of these three node densities are basically the same. The position at $2r$ from the sink node is a critical point. When the distance is greater than $2r$, the data transmission success rate of the node changes very slowly, otherwise it changes rapidly.

VII. CONCLUSION

A large number of sensing devices are broadly used in industry, agriculture, environmental protection, national defense, security, social life and many other fields, and has profoundly affected all aspects of human life. With the development of micro-processing technology, the volume of sensing devices is smaller, while the accuracy, range and type of sensing physical characteristics are continuously improving, thereby greatly promoting the improvement of life quality of people. Cooperative communication between sensing devices is the key technology of the systems which dominates the performance and energy harvesting based on energy saving and rational use of the system, so it is of great significance to optimize the MAC protocol. The proposed GV-ACW MAC protocol improves network performance by controlling the size of the contention window. Compared with the existing research work, it has the following advantages: (1) Longer network lifetime. Based on alternative energy harvesting of energy rational use of different nodes in far or near area from the sink nodes, the lifetime of the network under the proposed protocol is longer than that of S-MAC and T-MAC protocols. (2) Higher energy utilization rate (alternatively equivalent to energy harvesting). The GV-ACW MAC protocol makes full use of the energy of nodes far away from the sink, thereby improving the energy utilization without reducing the network lifetime. (3) Higher data transmission success rate. In the area with sufficient energy, a larger contention window is used to reduce the conflicts, which decreases the retransmissions of nodes and the network delay, thereby improving the transmission success rate in the network. (4) Smaller average network delay. By changing the size of the contention window for nodes at the edge of network, the average delay of the network is reduced.

REFERENCES

[1] M. Yu, A. Liu, N. N. Xiong, and T. Wang, "An intelligent game based offloading scheme for maximizing benefits of IoT-edge-cloud ecosystems," *IEEE Internet Things J.*, early access, Nov. 23, 2020, doi: 10.1109/JIOT.2020.3039828.

[2] M. Ahmad, A. A. Ikram, I. Wahid, F. Ullah, and A. Ahmad, "Optimized clustering in vehicular ad hoc networks based on honey bee and genetic algorithm for Internet of Things," *Peer Peer Netw. Appl.*, vol. 13, no. 2, pp. 532–547, Mar. 2020.

[3] X. Zhu, Y. Luo, A. Liu, M. Z. A. Bhuiyan, and S. Zhang, "Multiagent deep reinforcement learning for vehicular computation offloading in IoT," *IEEE Internet Things J.*, early access, Nov. 26, 2020, doi: 10.1109/JIOT.2020.3040768.

[4] S. Huang, Z. Zeng, K. Ota, M. Dong, T. Wang, and N. Xiong, "An intelligent collaboration trust interconnections system for mobile information control in ubiquitous 5G networks," *IEEE Trans. Netw. Sci. Eng.*, early access, Nov. 17, 2020, doi: 10.1109/TNSE.2020.3038454.

[5] 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, Apr. 2019, doi: 10.1016/j.jnca.2019.01.022.

[6] W. Huang, K. Ota, M. Dong, T. Wang, S. Zhang, and J. Zhang, "Result return aware offloading scheme in vehicular edge networks for IoT," *Comput. Commun.*, vol. 164, pp. 201–214, Dec. 2020.

[7] A. Li, W. Liu, S. Zhang, and M. Xie, "Fast multicast with adjusting transmission power and active slots in software define IoT," *IEEE Access*, vol. 8, pp. 226352–226369, 2020.

[8] M. Z. Uddin, M. M. Hassan, A. Alsanad, and C. Savaglio, "A body sensor data fusion and deep recurrent neural network-based behavior recognition approach for robust healthcare," *Inf. Fusion*, vol. 55, pp. 105–115, Mar. 2020, doi: 10.1016/j.inffus.2019.08.004.

[9] M. Aazam, S. Zeadally, and K. A. Harras, "Health fog for smart healthcare," *IEEE Consum. Electron. Mag.*, vol. 9, no. 2, pp. 96–102, Mar. 2020, doi: 10.1109/MCE.2019.2953749.

[10] X. Xu, N. Zhang, H. Song, A. Liu, M. Zhao, and Z. Zeng, "Adaptive beaconing based MAC protocol for sensor based wearable system," *IEEE Access*, vol. 6, pp. 29700–29714, 2018, doi: 10.1109/ACCESS.2018.2843762.

[11] F. R. Hsu, Y.-H. Kuo, S.-Y. Wei, Y.-H. Hsieh, and D. C. Nguyen, "A study of user interface with wearable devices based on computer vision," *IEEE Consum. Electron. Mag.*, vol. 9, no. 1, pp. 43–48, Jan. 2020, doi: 10.1109/MCE.2019.2941463.

[12] B. Manickavasagam and B. Amutha, "Analysis of efficient unmanned aerial vehicles to handle medical emergency data transmission surveillance system by using wireless body area network," *Comput. Commun.*, vol. 152, pp. 19–33, Feb. 2020, doi: 10.1016/j.comcom.2020.01.022.

[13] J. Gui, X. Dai, and X. Deng, "Stabilizing transmission capacity in millimeter wave links by Q-learning-based scheme," *Mobile Inf. Syst.*, vol. 2020, pp. 1–17, Feb. 2020, doi: 10.1155/2020/7607316.

[14] X. Zhu, Y. Luo, A. Liu, W. Tang, and M. Z. A. Bhuiyan, "A deep learning-based mobile crowdsensing scheme by predicting vehicle mobility," *IEEE Trans. Intell. Transp. Syst.*, early access, Oct. 7, 2020, doi: 10.1109/TITS.2020.3023446.

[15] K. A. Hafeez, L. Zhao, B. Ma, and J. W. Mark, "Performance analysis and enhancement of the DSRC for VANET's safety applications," *IEEE Trans. Veh. Technol.*, vol. 62, no. 7, pp. 3069–3083, Sep. 2013, doi: 10.1109/TVT.2013.2251374.

[16] T. Li, A. Liu, N. N. Xiong, S. Zhang, and T. Wang, "A trustworthiness-based vehicular recruitment scheme for information collections in distributed networked systems," *Inf. Sci.*, vol. 545, pp. 65–81, Feb. 2021.
[17] G. Li, F. Li, T. Wang, J. Gui, and S. Zhang, "Bi-adjusting duty cycle for green communications in wireless sensor networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2020, no. 1, pp. 1–55, Dec. 2020, doi: 10.1186/s13638-020-01767-5.
[18] Y. Liu, K. Ota, K. Zhang, M. Ma, N. Xiong, A. Liu, and J. Long, "QTSAC: An energy-efficient MAC protocol for delay minimization in wireless sensor networks," *IEEE Access*, vol. 6, pp. 8273–8291, 2018, doi: 10.1109/ACCESS.2018.2809501.
[19] I. Syed, S.-H. Shin, B.-H. Roh, and M. Adnan, "Performance improvement of QoS-enabled WLANs using adaptive contention window backoff algorithm," *IEEE Syst. J.*, vol. 12, no. 4, pp. 3260–3270, Dec. 2018, doi: 10.1109/JSYST.2017.2694859.
[20] Y. Cheng, H. Zhou, and D. Yang, "CA-CWA: Channel-aware contention window adaption in IEEE 802.11ah for soft real-time industrial applications," *Sensors*, vol. 19, no. 13, p. 3002, Jul. 2019.
[21] Y. Rao, C. Deng, G. Zhao, Y. Qiao, L.-Y. Fu, X. Shao, and R.-C. Wang, "Self-adaptive implicit contention window adjustment mechanism for QoS optimization in wireless sensor networks," *J. Netw. Comput. Appl.*, vol. 109, pp. 36–52, May 2018, doi: 10.1016/j.jnca.2018.03.001.
[22] X. Liu, M. S. Obaidat, C. Lin, T. Wang, and A. Liu, "Movement-based solutions to energy limitation in wireless sensor networks: State of the art and future trends," *IEEE Netw.*, early access, Sep. 30, 2020, doi: 10.1109/MNET.011.2000445.
[23] Y. Liu, T. Wang, S. Zhang, X. Liu, and X. Liu, "Artificial intelligence aware and security-enhanced traceback technique in mobile edge computing," *Comput. Commun.*, vol. 161, pp. 375–386, Sep. 2020.
[24] B. Liang, X. Liu, H. Zhou, V. C. M. Leung, A. Liu, and K. Chi, "Channel resource scheduling for stringent demand of emergency data transmission in WBANs," *IEEE Trans. Wireless Commun.*, early access, Dec. 8, 2020, doi: 10.1109/TWC.2020.3041471.
[25] D. Zhang, R. Shen, J. Ren, and Y. Zhang, "Delay-optimal proactive service framework for block-stream as a service," *IEEE Wireless Commun. Lett.*, vol. 7, no. 4, pp. 598–601, Aug. 2018.
[26] W. Mo, T. Wang, S. Zhang, and J. Zhang, "An active and verifiable trust evaluation approach for edge computing," *J. Cloud Comput.*, vol. 9, no. 1, pp. 1–8, Dec. 2020, doi: 10.1186/s13677-020-00202-w.
[27] C. Zhou, Y. Gu, X. Fan, Z. Shi, G. Mao, and Y. D. Zhang, "Direction-of-arrival estimation for coprime array via virtual array interpolation," *IEEE Trans. Signal Process.*, vol. 66, no. 22, pp. 5956–5971, Nov. 2018.
[28] Y. Ren, Z. Zeng, T. Wang, S. Zhang, and G. Zhi, "A trust-based minimum cost and quality aware data collection scheme in P2P network," *Peer Peer Netw. Appl.*, vol. 13, no. 6, pp. 2300–2323, Nov. 2020.
[29] Y. Liu, X. Liu, A. Liu, N. N. Xiong, and F. Liu, "A trust computing-based security routing scheme for cyber physical systems," *ACM Trans. Intell. Syst. Technol.*, vol. 10, no. 6, Dec. 2019, Art. no. 61, doi: 10.1145/3321694.
[30] S. Huang, J. Gui, T. Wang, and X. Li, "Joint mobile vehicle–UAV scheme for secure data collection in a smart city," *Ann. Telecommun.*, pp. 1–22, Aug. 2020, doi: 10.1007/s12243-020-00798-9.
[31] O. Yan, A. Liu, N. Xiong, and T. Wang, "An effective early message ahead join adaptive data aggregation scheme for sustainable IoT," *IEEE Trans. Netw. Sci. Eng.*, early access, Oct. 29, 2020, doi: 10.1109/TNSE.2020.3033938.
[32] D. Zhang, L. Tan, J. Ren, M. K. Awad, S. Zhang, Y. Zhang, and P.-J. Wan, "Near-optimal and truthful online auction for computation offloading in green edge-computing systems," *IEEE Trans. Mobile Comput.*, vol. 19, no. 4, pp. 880–893, Apr. 2020.
[33] D. Zhang, Y. Qiao, L. She, R. Shen, J. Ren, and Y. Zhang, "Two timescale resource management for green Internet of Things networks," *IEEE Internet Things J.*, vol. 6, no. 1, pp. 545–556, Feb. 2019.
[34] S. Huang, A. Liu, S. Zhang, T. Wang, and N. Xiong, "BD-VTE: A novel baseline data based verifiable trust evaluation scheme for smart network systems," *IEEE Trans. Netw. Sci. Eng.*, early access, Aug. 7, 2020, doi: 10.1109/TNSE.2020.3014455.
[35] X. Li, J. Tan, A. Liu, P. Vijayakumar, N. Kumar, and M. Alazab, "A novel UAV-enabled data collection scheme for intelligent transportation system through UAV speed control," *IEEE Trans. Intell. Transp. Syst.*, early access, Dec. 17, 2020, doi: 10.1109/TITS.2020.3040557.
[36] D. Zhang, Z. Chen, L. X. Cai, H. Zhou, S. Duan, J. Ren, X. Shen, and Y. Zhang, "Resource allocation for green cloud radio access networks with hybrid energy supplies," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1684–1697, Feb. 2018.
[37] Q. Liu, P. Hou, G. Wang, T. Peng, and S. Zhang, "Intelligent route planning on large road networks with efficiency and privacy," *J. Parallel Distrib. Comput.*, vol. 133, pp. 93–106, Nov. 2019.
[38] 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. 2018.
[39] Q. Tang, H. Lyu, G. Han, J. Wang, and K. Wang, "Partial offloading strategy for mobile edge computing considering mixed overhead of time and energy," *Neural Comput. Appl.*, vol. 32, no. 19, pp. 15383–15397, Oct. 2020, doi: 10.1007/s00521-019-04401-8.
[40] T.-J. Tsai and J.-W. Chen, "IEEE 802.11 MAC protocol over wireless mesh networks: Problems and perspectives," in *Proc. 19th Int. Conf. Adv. Inf. Netw. Appl. (AINA)*, Taipei, Taiwan, vol. 1, 2005, pp. 60–63, doi: 10.1109/AINA.2005.206.
[41] I. F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "Wireless sensor networks: A survey," *Comput. Netw.*, vol. 38, no. 4, pp. 393–422, Mar. 2002, doi: 10.1016/S1389-1286(01)00302-4.
[42] W. Ye, J. Heidemann, and D. Estrin, "An energy-efficient MAC protocol for wireless sensor networks," in *Proc. 21st Annu. Joint Conf. IEEE Comput. Commun. Societies*, New York, NY, USA, vol. 3, 2002, pp. 1567–1576, doi: 10.1109/INFCOM.2002.1019408.
[43] T. van Dam and K. Langendoen, "An adaptive energy-efficient MAC protocol for wireless sensor networks," in *Proc. 1st Int. Conf. Embedded Netw. Sensor Syst. (SenSys)*. New York, NY, USA: ACM, 2003, pp. 171–180, doi: 10.1145/958491.958512.
[44] K. Jamieson, H. Balakrishnan, and Y. C. Tay, "Sift: A MAC protocol for event-driven wireless sensor networks," in *Proc. 3rd Eur. Conf. Wireless Sensor Netw. (EWSN)*. Berlin, Germany: Springer-Verlag, 2006, pp. 260–275, doi: 10.1007/11669463_20.
[45] V. Rajendran, J. J. Garcia-Luna-Aceves, and K. Obraczka, "Energy-efficient channel access scheduling for power-constrained networks," in *Proc. 5th Int. Symp. Wireless Pers. Multimedia Commun.*, Honolulu, HI, USA, vol. 2, 2002, pp. 509–513, doi: 10.1109/WPMC.2002.1088226.
[46] P. Havinga and L. Van Hoesel, "A lightweight medium access protocol (LMAC) for wireless sensor networks: Reducing preamble transmissions and transceiver state switches," in *Proc. 1st Int. Conf. Netw. Sensing Syst. (INSS)*, Tokyo, Japan, 2004, pp. 205–208.
[47] S. Chatterjea, L. F. W. van Hoesel, and P. J. M. Havinga, "AI-LMAC: An adaptive, information-centric and lightweight MAC protocol for wireless sensor networks," in *Proc. Intell. Sensors, Sensor Netw. Inf. Process. Conf.*, Melbourne, VIC, Australia, 2004, pp. 381–388, doi: 10.1109/ISSNIP.2004.1417492.
[48] V. Rajendran, K. Obraczka, and J. J. Garcia-Luna-Aceves, "Energy-efficient, collision-free medium access control for wireless sensor networks," *Wireless Netw.*, vol. 12, no. 1, pp. 63–78, Feb. 2006, doi: 10.1007/s11276-006-6151-z.
[49] S. Singh and C. S. Raghavendra, "PAMAS—Power aware multi-access protocol with signalling for ad hoc networks," *ACM SIGCOMM Comput. Commun. Rev.*, vol. 28, no. 3, pp. 5–26, Jul. 1998.
[50] Y. Kwon, Y. Fang, and H. Latchman, "A novel MAC protocol with fast collision resolution for wireless LANs," in *Proc. 22nd IEEE Annu. Joint Conf. IEEE Comput. Commun. Societies (INFOCOM)*, San Francisco, CA, USA, vol. 2, Mar. 2003, pp. 853–862, doi: 10.1109/INFCOM.2003.1208923.
[51] *IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, IEEE Standard 802.11-1997, Nov. 1997, pp. 1–445, doi: 10.1109/IEEESTD.1997.85951.
[52] S. Liu, G. Huang, J. Gui, T. Wang, and X. Li, "Energy-aware MAC protocol for data differentiated services in sensor-cloud computing," *J. Cloud Comput.*, vol. 9, no. 1, Aug. 2020, Art. no. 48, doi: 10.1186/s13677-020-00196-5.
[53] L. Bononi, M. Conti, and L. Donatiello, "Design and performance evaluation of a distributed contention control (DCC) mechanism for IEEE 802.11 wireless local area networks," *J. Parallel Distrib. Comput.*, vol. 60, no. 4, pp. 407–430, Apr. 2000, doi: 10.1006/jpdc.1999.1612.
[54] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Sel. Areas Commun.*, vol. 18, no. 3, pp. 535–547, Mar. 2000, doi: 10.1109/49.840210.
[55] F. Lyu, H. Zhu, H. Zhou, L. Qian, W. Xu, M. Li, and X. Shen, "MoMAC: Mobility-aware and collision-avoidance MAC for safety applications in VANETs," *IEEE Trans. Veh. Technol.*, vol. 67, no. 11, pp. 10590–10602, Nov. 2018.
[56] X. Liu, H. Song, and A. Liu, "Intelligent UAVs trajectory optimization from space-time for data collection in social networks," *IEEE Trans. Netw. Sci. Eng.*, early access, Aug. 19, 2020, doi: 10.1109/TNSE.2020.3017556.

[57] X. Liu, P. Lin, T. Liu, T. Wang, A. Liu, and W. Xu, "Objective-variable tour planning for mobile data collection in partitioned sensor networks," *IEEE Trans. Mobile Comput.*, early access, Jun. 1, 2020, doi: 10.1109/TMC.2020.3003004.

[58] M. Shen, A. Liu, G. Huang, N. N. Xiong, and H. Lu, "ATTDC: An active and trace-able trust data collection scheme for industrial security in smart cities," *IEEE Internet Things J.*, early access, Jan. 5, 2021, doi: 10.1109/JIOT.2021.3049173.

[59] *OMNET++ Network Simulation Framework*. Accessed: Jun. 8, 2019. [Online]. Available: http://www.omnetpp.org

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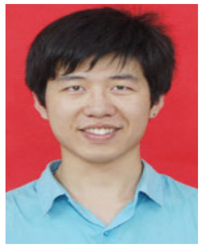

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