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SPECIAL SECTION ON ADVANCED COMMUNICATIONS AND NETWORKING TECHNIQUES FOR WIRELESS CONNECTED INTELLIGENT ROBOT SWARMS

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Research on Election Interval of Distributed Wireless Ad Hoc Networks

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ABSTRACT The distributed scheduling mode possesses numerous advantages over the centralized scheduling mode in scenarios where the topology changes rapidly, such as low operation and maintenance costs, high robustness and improved delay performance, and thus has broad application prospects in robot swarms, device-to-device networks, industrial sensor networks, etc. The distributed election mechanism can effectively reduce collisions and improve the success probability of random access, which is one of the most commonly used channel access methods in distributed networks. The size of election interval directly affects the probability of successful election and the network performance. Specifically, with the expansion of the network scale, smaller election intervals will lead to more election nodes and reduce the probability of successful elections. Although expanding the election interval can reduce collisions to a certain extent, the number of legal election nodes will increase, which reduces the probability of successful elections. Therefore, the choice of the election interval needs to be explored in detail. This paper analyzes the relationship between the election interval and the number of effective election nodes, and establishes the analytical model of the election success probability, scheduling delay and effective throughput. In addition, the election interval size and the number of control slots are optimized to improve effective throughput and delay performance. Finally, the impact of the election interval on the network performance is verified by simulation, which provides guidance for parameter selection in realistic scenarios.

INDEX TERMS Distributed wireless ad hoc networks, election interval, optimal number of control slots.

I. INTRODUCTION

A. MOTIVATION

With the development of artificial intelligence in recent years, robot swarms have become a research hotspot in the field of artificial intelligence. The communication between multiple robots lays the foundation for the reliable and effective operation of robot swarms [1]. The distributed ad hoc network is a peer-to-peer network, in which the failure of individual nodes will not affect the operation of the entire network. Compared with centralized networks, distributed networks only need local information exchange, which can effectively reduce maintenance cost and improve network scalability, and thus has broad application prospects in robot swarms, 5G networks, device-to-device networks, industrial sensor networks, etc. With the development of intelligent interconnection technology, distributed ad hoc networks provide new ideas for the communication of robot swarms. Therefore, the research and development of distributed networking mode is imperative [2].

B. RELATED WORK

The distributed election mechanism is one of the most commonly used channel access methods of distributed networks, which can effectively reduce collisions compared with carrier sense multiple access with collision avoidance (CSMA/CA) [3]. The size of the election interval directly affects the probability of successful election, which is defined as the probability that a node successfully obtains the right to transmit in a given time slot when competing with other nodes. When the election interval is small, the probability of election success decreases as the node density increases. The extension of the election interval can increase the probability of successful election, but it will also increase the number of election nodes, which is not conducive to the improvement

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of network performance. However, the election interval is not clearly specified in the agreement [4] and is usually assumed infinite for the sake of convenience [5], [6]. Therefore, it is imperative to explore the impact of the election interval in detail.

[7]–[9] establish the delay and throughput models for distributed wireless networks to assess the impact of network parameters under the assumption that the election interval for the distributed election mechanism is infinite. Therefore, the impact of the election interval is not considered. [10] proposes a method of dynamically adjusting the backoff index *XmtHoldoffExp* during the election process, that is, different nodes are assigned different back-off indices according to the activity level of the nodes, so that the active nodes can have a higher chance of obtaining transmission opportunities. It improves the throughput of the network to a certain extent. However, it does not consider the overall delay performance deterioration caused by the long-term inability of some nodes to occupy the channel. [11] proposes a method of dynamically adjusting the back-off index according to service priority, which can reduce the contention time of some nodes in the network and improve the network throughput to a certain extent. However, it does not consider the effect of the interval size on the number of nodes which participates in the election process and the optimization of the delay performance. [12], [13] establish the scheduling delay model of distributed wireless ad hoc networks based on the election mechanism. It is shown that the size of the back-off index can affect the number of time slots waiting between two transmissions, which affects the performance of the network. However, it does not study the impact of the specific interval size, and did not conduct further research on performance optimization. [14] proposes a dynamic adjustment scheme of back-off duration to make the network suitable for different network densities and improve the network performance when the network node density changes dynamically. However, it mainly focuses on the impact of the back-off index on network performance and ignores the impact of the election interval and the proportion of control time slots on network performance. [15] proposes a resource scheduling algorithm for allocating channels based on the data length of the MAC layer, which eliminates network conflicts to a certain extent and improves the scheduling delay of the network, but it has not considered the impact of the election interval during the network access process. [16] uses a three-dimensional Markov chain model to analyze the saturated throughput of each data stream in the network, but it ignores the influence of the election interval on the throughput during the message interaction process.

C. CONTRIBUTION

Regarding the aforementioned problems, we analyze the relationship between the election interval and the number of effective election nodes for distributed wireless multi-hop networks and establish the delay and throughput model considering election interval, node density, and traffic volume.

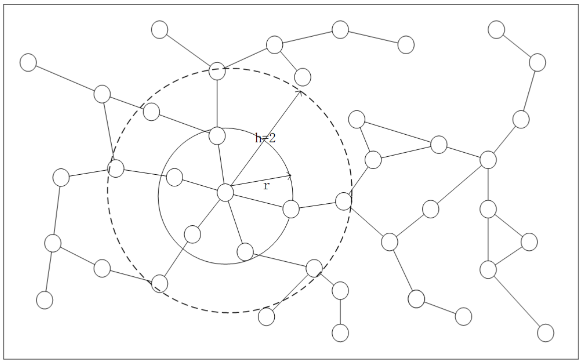

FIGURE 1. An example of the distributed ad hoc network model.

In addition, we optimize the election interval size and the ratio of the number of control slots and the number of data slots, denoted as C/D, to improve the effective throughput and delay performance. Finally, we verify the impact of the election interval on network performance by simulation, which provides guidance for the selection of parameters in realistic scenarios.

The structure of this paper is organized as follows. Section II reviews the system model. Section III derives the analytical model of the distributed election mechanism. Section IV demonstrates the numerical results while section V concludes the paper.

II. SYSTEM MODEL

A. NETWORK MODEL

An example of the network model is given in Fig. 1. We assume that nodes are uniformly distributed and the node density is ρ. Each node maintain its h-hops neighbors based on the exchange of the distributed scheduling message (DSCH). Therefore, the total number of neighbors for each node is $N = \pi(hr)^2\rho$, where r denotes the communication radius of one hop.

B. FRAME STRUCTURE

The frame structure of the media access control (MAC) layer is given in Fig. 2. In the MAC layer, time is divided into frames. Each frame has time duration T_F and is divided into n_F equal-length time slots, in which C slots are used for control message transmission and are referred to as control slots, while D slots are used for data transmission and are referred to as data slots. We have $n_F = C + D$. The control slots form the control subframe whereas the data slots form the data subframe.

C. DISTRIBUTED ELECTION MECHANISM

The distributed election mechanism is one of the most commonly used channel access methods of distributed ad hoc networks. We provide the discussion on the DSCH message, which is used for scheduling message transmission, as an example to illustrate the distributed election mechanism [17]. After each successful transmission, a node will randomly

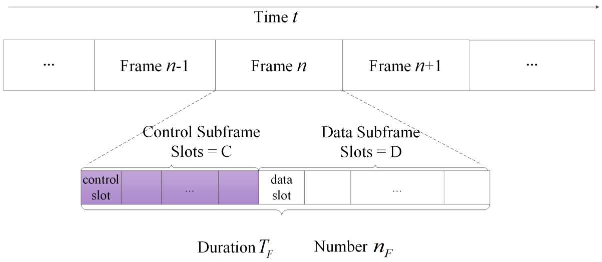

FIGURE 2. **Frame Structure of the MAC layer.**

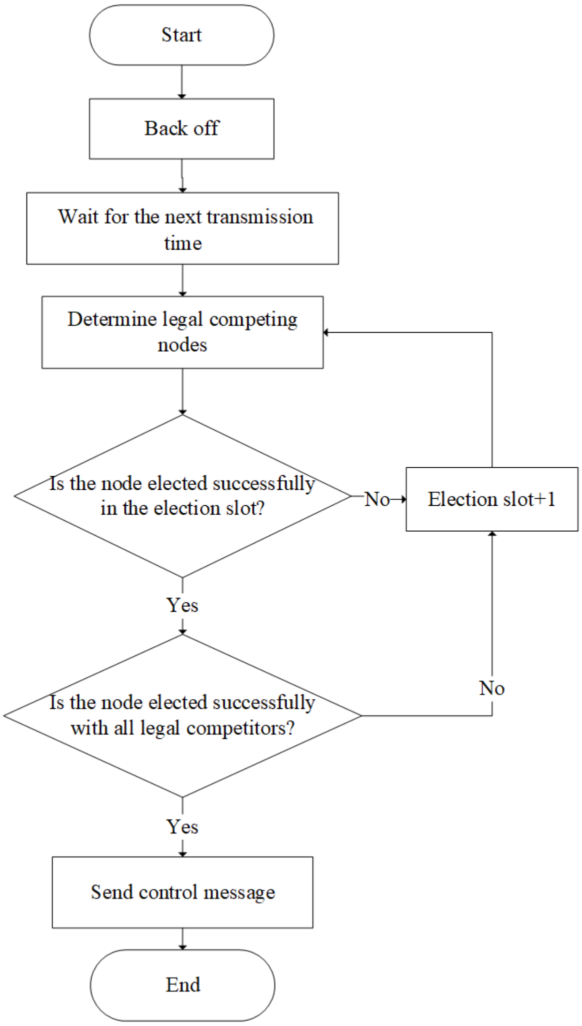

FIGURE 3. **Election mechanism process.**

back-off and wait for the next transmission time. This node elects the next transmission slot when a DSCH message is sent. All legally competitive nodes use a pseudo-random algorithm to elect the first idle time slot after random back-off. If the election is successful, the next transmission time is determined. If the node fails the election process in this time slot, the node increases the idle time slot by one and continues to elect until it succeeds. The process of the election mechanism is illustrated in Fig. 3.

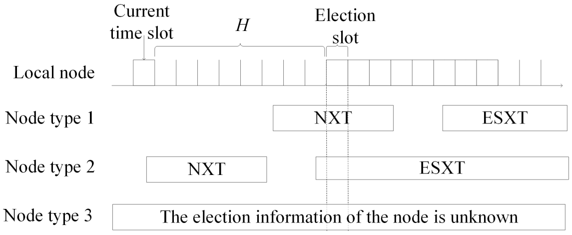

FIGURE 4. **Description of the legal competition node.**

The rules for determining legitimate competing nodes affect the number of nodes which participate in the election process. Each node performs neighbor maintenance and resource scheduling by receiving the DSCH message from its neighbors. The DSCH message carries two parameters $NextXmtMx(NXM)$ and $XmtHoldoffExponet(Exp)$ to calculate the next sending time of the neighbor (NXT) and to predict the earliest next transmission time ($ESXT$).

The range of the next transmission time NXT follows

$$2^{Exp} \times NXM < NXT \leq 2^{Exp} \times (NXM + 1) \tag{1}$$

The range of the earliest next transmission time $ESXT$ is expressed as

$$ESXT = NXT + H \tag{2}$$

in which $H = 2^{Exp+Basic}$, $Basic = 4$.

The legal competition nodes mainly include:

- The nodes whose NXT contain the election time slot, which are depicted as node type 1 in Fig. 4.
- The nodes whose $ESXT$ contain the election time slot, which are depicted as node type 2 in Fig. 4.
- The nodes whose election information are unknown, which are depicted as node type 3 in Fig. 4.

III. ANALYTICAL MODEL OF DISTRIBUTED ELECTION MECHANISM

This section analyzes the election interval and its impact on the election success probability. The analytical models of the delay and effective throughput of the distributed election mechanism are also derived. The optimal election interval is obtained by minimizing the delay while the optimal C/D ratio is obtained by maximizing the effective throughput.

A. ELECTION SUCCESS PROBABILITY

The size of the election interval affects the access success probability of the scheduling message, which affects the MAC layer scheduling delay and effective throughput. Networks with different node densities also have different requirements for the size of the election interval. To ensure the validity and reliability of the network, we analyze the value of the election interval under different network node densities.

At present, theoretical studies usually regard the election interval as infinite for the convenience of analysis and calculation, which is questionable for practical scenarios. The IEEE 802.16 protocol limits the range of the next transmission time, i.e., sets the maximum election interval. Here we

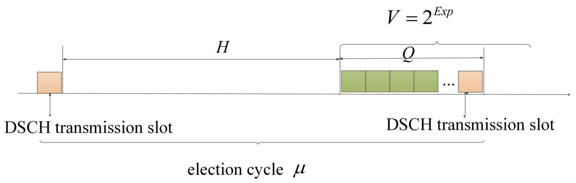

FIGURE 5. Diagram of the limited election process.

further explore the election process and derive an analytical model of the election interval. Fig. 5 shows the election process with limited election boundaries. The node starts the election in the first time slot when the back-off process is completed. If the election is unsuccessful, the current time slot is incremented by one and the election process continues.

We define the size of the election interval as $V = 2^{Exp}$, which is specified in the number of slots. Therefore, the key to determining the size of the election interval is the selection of back-off index *Exp*, which should be adjusted according to the network density. In order to ensure the fairness between nodes, the same back-off index should be assumed for each node, and the value of the back-off index should ensure that all valid competing nodes in the election interval have the same probability to conduct the election process.

Let Q denote the election length, which represents the number of time slots needed for one node from the end of the back-off process to the next successful competition, and we have $0 \le Q \le V$ in consideration of the limited election interval. Without loss of generality, we conduct the analysis for a given node. It starts competing immediately after the back-off is completed. Under steady-state conditions, we assume the node has the same probability of election success in each slot. Therefore, the probability mass function of Q is expressed as

$$P(Q = q) = (1-p)^{q-1}p, \quad q \in (0, V] \tag{3}$$

where p denotes the election success probability in each slot.

The expectations of the election interval Q is thus given as

$$E(Q) = \sum_{q=1}^{V} qP(Q = q) = \frac{1}{p} - (\frac{1}{p} - V)(1-p)^V \tag{4}$$

Therefore, the election cycle of the node is expressed as

$$\mu = H + E(Q) = H + \frac{1}{p} - (\frac{1}{p} - V)(1-p)^V \tag{5}$$

where H denotes the length of the back-off process specified in the number of slots, and $V = 2^{Exp}$.

The probability of election success p in each slot is determined by the number of nodes participating in the election in each slot, which is denoted as N_{cp} in the following analysis. We have $N_{cp} = Np_{cp}$, in which N denotes the number of neighbors for each node while p_{cp} denotes the probability that a node becomes an election node in a given time slot. p_{cp} is affected by the election cycle μ and the probability of election success in each slot p. According to [12], given that the election interval is q, the probability that a node becomes an election node in a given time slot is expressed as

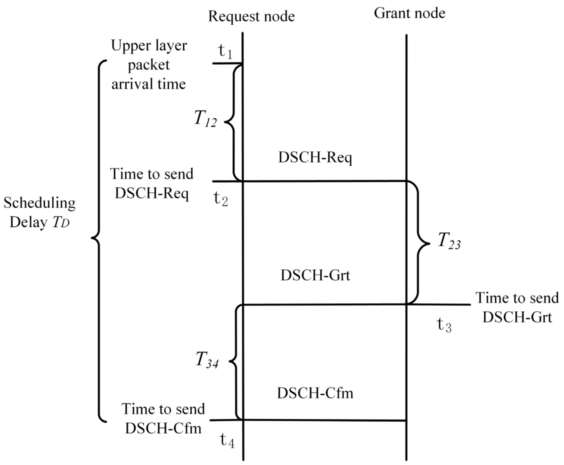

FIGURE 6. Illustration of the scheduling process.

$$p_{cp}(q) = \frac{V}{\mu} + \frac{1-(1-p)^q}{\mu p} - \frac{q}{\mu}(1-p)^V, \quad 0 \le q \le V \tag{6}$$

where μ is given in (5).

The node starts competing immediately after the back-off. For any control slot, as long as the parameters *Exp* of all the competing nodes are equal, the probability that these nodes succeed in competing for this slot is equal. Therefore,

$$p = \frac{1}{E(Np_{cp})} \tag{7}$$

Based on (7), the probability that a node succeeds in the election process in a given time slot is p obtained as

$$p = \frac{-1-\sqrt{3}i}{2}\sqrt[3]{-d + \sqrt{d^2 + (\frac{3ac-b^2}{9a^2})^3}} + \frac{-1+\sqrt{3}i}{2}\sqrt[3]{-d - \sqrt{d^2 + (\frac{3ac-b^2}{9a^2})^3}} - \frac{b}{3a} \tag{8}$$

in which N denotes the total number of nodes in the network, $a = V - VN - H, b = 2VN - 2V + 3H - 1, c = N - 2H + 2$, $d = -a^{-1} - \frac{1}{6}a^{-2}bc + \frac{1}{27}a^{-3}b^3$.

B. SCHEDULING DELAY

The scheduling process works as follows: the MAC layer of the sending node randomly receives the data packet sent by the upper layer (or the MAC layer receives the resource request sent by the upper layer); the sending node performs the reservation negotiation with the receiving node using the DSCH control message; the sending node sends the confirmation message to the receiving node. The scheduling process is shown in Fig. 6.

The scheduling delay of the MAC layer includes three parts: request delay, authorization delay, and acknowledgment delay. It can be expressed as

$$T_D = T_{12} + T_{23} + T_{34} \tag{9}$$

in which T_{12} denotes the time interval from the reception of data packet from the upper layer to the successful transmission of the request message, T_{23} denotes the time interval from the reception of the request message to the successful transmission of the authorization message, and T_{34} denotes the time interval from the reception of the authorization message to the successful transmission of the acknowledgment message.

First we give a detailed analysis of T_{12}. For $1 \leq T_{12} \leq H$, the probability of $T_{12} = i$ is expressed as

$$\begin{aligned} p_{1\rightarrow H,i} = p\frac{1}{H+1} + p(1-p)\frac{1}{H+2} + p(1-p)^2\frac{1}{H+3} \\ + \cdots + p(1-p)^{V-1}\frac{1}{H+V} \end{aligned} \tag{10}$$

For $H+1 \leq T_{12} \leq H+V$, the probability of $T_{12} = i$ is expressed as

$$\begin{aligned} p_{H+1\rightarrow H+V,i} = p(1-p)^{i-1}\frac{1}{H+i} + p(1-p)^{i}\frac{1}{H+i+1} \\ + \cdots + p(1-p)^{V-1}\frac{1}{H+V} \end{aligned} \tag{11}$$

T_{12} is thus obtained as

$$\begin{aligned} T_{12} &= \sum_{i=1}^{H} ip_{1\rightarrow H,i} + \sum_{i=H+1}^{H+V} ip_{H+1\rightarrow H+V,i} \\ &= \frac{H(H+1)p}{2(1-p)^H}\int_0^{1-p}\frac{x^{H-1}-x^{H+V-1}}{1-x}dx + \frac{1-p}{p} \end{aligned} \tag{12}$$

The authorization process and the acknowledgment process are the same as the request process, which are also determined by the random arrival of the message and the election access process. We assume that the request delay, authorization delay, and acknowledgement delay are equal. Therefore,

$$T_{12} = T_{23} = T_{34} \tag{13}$$

The MAC layer scheduling delay T_D is thus obtained as

$$T_D = \frac{3H(H+1)p}{2(1-p)^H}\int_0^{1-p}\frac{x^{H-1}-x^{H+V-1}}{1-x}dx + \frac{3(1-p)}{p} \tag{14}$$

To minimize the scheduling delay given in (14), the optimal value of the back-off index is obtained as

$$Exp_{optimal} = \lceil log_2(\pi(hr)^2\rho)\rceil \tag{15}$$

C. EFFECTIVE THROUGHPUT

As pointed out in [15], effective throughput reflects the ability of each node in the network to send its own service, and is one of the most important indicators of the network performance. Here we assume that all N nodes have service data to transmit.

Under the infinite election interval assumption, all nodes will eventually succeed in the competition for resources. Therefore, all nodes are considered when calculating the throughput. From [17], the effective throughput of the MAC layer is given as

$$R_{inf} = \frac{2DW(N-1)}{n_F(2(N-1)+(2+\pi r^2\rho)(M-1)k+M\pi r^2\rho)} \tag{16}$$

where M denotes the number of network data streams, W denotes the data slot bandwidth, and $k = \frac{(ln(N)-ln(\pi r^2\rho))}{ln(\pi r^2\rho)}$.

In comparison, under the limited election interval scenarios, some nodes may fail the election process in a given election interval, whose impact should be set aside when calculating the effective throughput. From the analysis in Sec. III-A, the effective throughput under the limited conditions of the election interval is given as

$$\begin{aligned} R_f &= (1-(1-p)^V)R_{inf} \\ &= \frac{2(1-(1-p)^V)(n_F-C)W(N-1)}{n_F(2(N-1)+(2+\pi r^2\rho)(M-1)k+M\pi r^2\rho)} \end{aligned} \tag{17}$$

From (17), we see that the effective throughput is affected by the node density, the number of data streams, and the number of control slots. When the number of data streams is fixed, the effective throughput first increases then decreases with the increase of the node density. The reason is that when the node density is small, all the nodes could succeed in the election process and transmit data, so that the effective throughput increases as the node density increases. In comparison, when the node density reaches a certain value, the number of nodes that fail the election process increases due to the limited election interval, which results in a decrease in effective throughput.

The total number of slots within each frame is fixed. Given the number of data streams and the length of the election interval, it is necessary to optimize the C/D ratio to obtain the highest effective throughput. When C is relatively small, the number of nodes which have successfully reserved transmission slots is limited by the number of control slots, which restrains the effective throughput. In comparison, when C is relatively large, the effective throughput is determined by the number of data slots, which are fully occupied and may be insufficient for data transmission. As a result, the optimal number of the control slots $\overline{C}$ given the limited election interval needs to be explored in detail to optimize the performance of the network system. Based on the above analysis, we see that the optimal value of C satisfies two conditions: the control slots that are used for transmission slot reservation are fully exploited; the data slots are fully occupied and are sufficient for the data transmission. We interpret these two conditions into the follow events [17]:

1) self-service transmission amount + forwarding data amount = total data volume of the maximum reservation time slot.
2) own traffic + forwarding data volume + two types of pseudo collision data = all data slots.

Based on the concurrence of the two events, we have the following simultaneous equations.

TABLE 1. **Parameter settings.**

Notation	Meaning	Value
ρ	Node density $(nodes/km^2)$	0-100
r	Effective communication radius (m)	250
h	Number of hops maintained by neighbors	2
Exp	Backoff index	0/1/2
$Basic$	Fixed backoff index	4
n_F	Total number of slots per frame	23
x	Maximum number of reserved slots	100

$$\begin{cases} R_f + \dfrac{(M-1)k}{N-1}R_f = [1-(1-p)^V]\dfrac{CxW}{T_D n_F} \\ \dfrac{\pi r^2 \rho}{2} \times \dfrac{(M-1)k+M}{N-1}R_f + [1-(1-p)^V]\dfrac{CxW}{T_D n_F} \\ = [1-(1-p)^V]\dfrac{DW}{n_F} \end{cases} \tag{18}$$

where x denotes the maximum number of time slots that can be reserved.

We obtain the optimal number of control slots by solving (18), which is given as

$$\overline{C} = \frac{T_D n_F}{T_D + x(1 + \frac{\pi r^2 \rho}{2} \times \frac{(M-1)k+M}{(N-1)+2(M-1)k})} \tag{19}$$

It can be seen that the optimal number of control slots is related to the network density and the number of service flows. When the number of service flow is small, the number of optimal control slots increases as the network density increases. This is because when the number of network service flows is constant, each node needs to bear less services when the number of nodes increases, and the channel occupation capacity is reduced, so $\overline{C}$ increases. When the number of service flow is large, the number of optimal control time slots increases at first and then decreases as the network density increases. When the number of nodes is small, the number of control time slots required increases with the increase of network density. When the number of nodes reaches a certain number, the number of forwarding and pseudo collisions that nodes need to bear increases. The network needs more data slots to maintain service transmission and $\overline{C}$.

IV. NUMERICAL ANALYSIS

In this section, we conduct analysis on the scheduling delay and the effective throughput. Table 1 shows the values of parameters.

Fig. 7 depicts the variation of the scheduling delay with the node density under different backoff index Exp. The election success probability is set to 0.8. Firstly, the scheduling delay increases as the node density increases for all the considered values of Exp. When the node density is less than 35 $nodes/km^2$, $Exp = 0$ leads to the the lowest network delay. The reason is that when the number of nodes is small, a small election interval is enough to satisfy the needs of node election. When the node density falls in $[35, 60] nodes/km^2$, $Exp = 1$ leads to the the lowest network delay. As the node density exceeds 60 $nodes/km^2$, $Exp = 2$ has the best delay performance. The reason is that when the number of nodes increases, the number of nodes participating in the election increases, and the smaller election interval cannot meet the election requirements of the node. Therefore, the value of the backoff index, i.e., the election interval, needs to be carefully designed based on the network size to achieve the best delay performance.

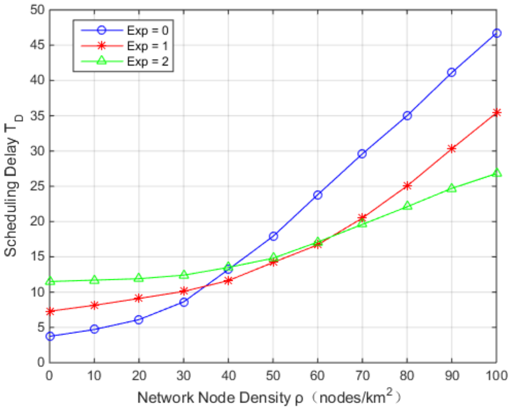

FIGURE 7. **The variation of the scheduling delay with network node density given Exp = 1,2,3.**

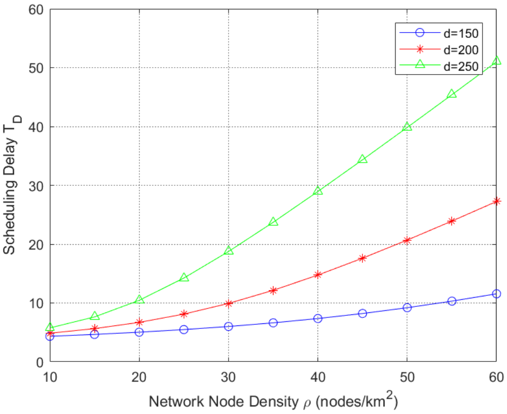

FIGURE 8. **The variation of the scheduling delay with network node density given d = 150,200,250.**

Fig. 8 depicts the relationship between scheduling delay under different effective communication distances. Under the same network node density, the larger the effective communication distance, the greater the delay. This is because as the communication distance increases, the number of neighbors in the neighbor maintenance range increases. Therefore, the number of competing nodes for the same time slot increases. The probability that a node will get a certain time slot will decrease, thereby increasing the delay. For the same reason, when the communication distance is fixed, as the node density increases, the scheduling delay also increases.

Fig. 9 depicts the relationship between scheduling delay and network node density under different maintenance

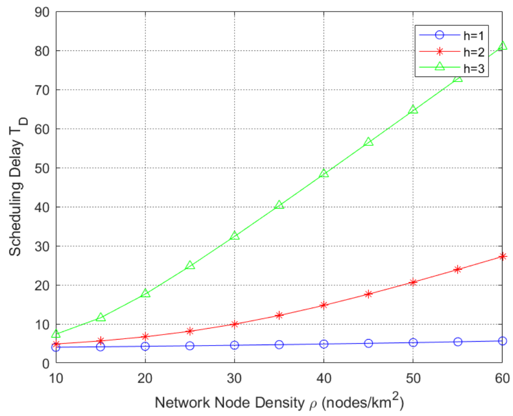

FIGURE 9. The variation of the scheduling delay with network node density given h = 1,2,3.

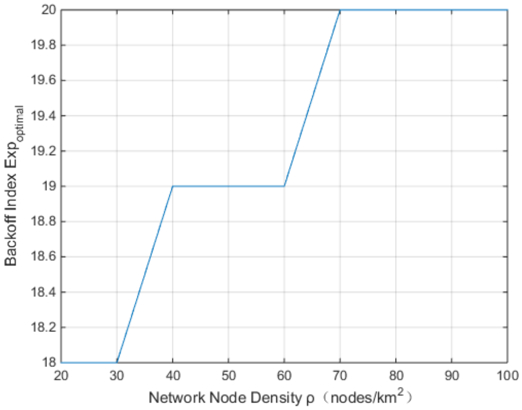

FIGURE 10. The optimal backoff index for different network node density.

ranges, i.e., hops maintained by neighbors. Under the same network node density, the larger the maintenance range, the greater the delay. This is because as the number of network maintenance hops increases, the number of neighbors in the maintenance range increases. Therefore, competing nodes for the same time slot will increase, so that the probability that a node gets a certain time slot will decrease, thereby increasing the delay.

Fig. 10 depicts the results of (15), i.e., the optimal value of *Exp* to minimize the scheduling delay. Since the election interval is $V = 2^{Exp}$, the backing index *Exp* is used to indicate the election interval. When the node density is $\rho \in (20node/km^2, 30node/km^2]$, the optimal back-off index is 0, and the election interval is 1. When the node density is $\rho \in (30node/km^2, 60node/km^2]$, the optimal back-off index is 1, and the size of the election interval is 2. When the node density is $\rho \in (60node/km^2, 90node/km^2]$, the optimal back-off index is 2, and the size of the election interval is 4. Therefore, the analytical results are consistent with the simulation results given in Fig. 7.

Fig. 11 depicts the variation of the effective throughput with the node density under different backoff index *Exp*. The node density is set to $\rho = 35node/km^2$, assuming that all nodes generate traffic. It is shown that $Exp = 1$ leads to the highest effect throughput. On the one hand, when the election interval is small, the number of nodes participating in the election is large, resulting in a high probability of node election failure and a small network throughput. On the other hand, when the election interval is large, the number of nodes participating in the election is relatively small, and the election success probability increases, but the increase in the election period results in a decrease in the effective throughput. Therefore, the intermediate value of $Exp = 1$ achieves the best performance. As the number of control slots increases, the effective throughput first increases and then decreases. When the number of control slots is less than the optimal value, the throughput gradually goes up as the C increases because more data slots can be utilized. When the number of control slots exceeds the optimal value, The throughput starts to decline when C exceeds its optimal value since control slots occupy too much channel resources.

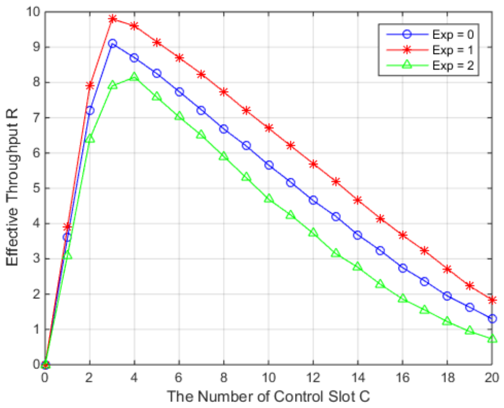

FIGURE 11. Relationship between the number of optimal control slots and effective throughput.

V. CONCLUSION

In this paper, we analyze the impact of the election interval in distributed wireless ad hoc networks. The results show that the value of election interval should be selected given the network node density to obtain the best delay performance. Moreover, given the node density, the ratio of the number of control slots and the number of data slots in each frame should be carefully designed to achieve the highest effective throughput. The results provide guidance for parameter settings in realistic scenarios. For future work, we would further optimize the analytical method of the distributed election mechanism to apply to more complex network scenarios.

REFERENCES

[1] K. Narayanan, V. Honkote, D. Ghosh, and S. Baldev, "Energy efficient communication with lossless data encoding for swarm robot coordination," in *Proc. 32nd Int. Conf. VLSI Design 18th Int. Conf. Embedded Syst. (VLSID)*, Delhi, India, Jan. 2019, pp. 525–526.

[2] E. Roth-Mandutz, A.-M. Waswa, and A. Mitschele-Thiel, "Capacity optimization for ultra-reliable low-latency communication in 5G—The SON perspective," in *Proc. 13th Int. Conf. Netw. Service Manage. (CNSM)*, Tokyo, Japan, Nov. 2017, pp. 1–8.

[3] S. Chakraborty, D. K. Sanyal, A. Chakraborty, A. Ghosh, S. Chattopadhyay, and M. Chattopadhyay, "Tuning holdoff exponents for performance optimization in IEEE 802.16 mesh distributed coordinated scheduler," in *Proc. 2nd Int. Conf. Comput. Autom. Eng. (ICCAE)*, Singapore, Feb. 2010, pp. 256–260.

[4] *IEEE Standard for WirelessMAN-Advanced Air Interface for Broadband Wireless Access Systems 2: Higher Reliability Networks*, IEEE Standard 802.16.1a-2013 (Amendment to IEEE Std 802.16.1-2012), 2013, pp. 1–319.

[5] H. Hamouda, M. O. Kabaou, and M. S. Bouhlel, "A cross-layer downlink scheduling scheme for balancing QoS in IEEE 802.16 broadband wireless access systems," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, Sep. 2017, pp. 1–5.

[6] X. Zhang and H. Zeng, "Research on data subframe scheduling in IEEE802.16 distributed mesh network," in *Proc. IEEE Int. Conf. Signal Process., Commun. Comput. (ICSPCC)*, Guilin, China, Aug. 2014, pp. 838–843.

[7] F. Zhang, Y. Cao, and D. Wang, "A note on 'Low-complexity distributed scheduling algorithms for wireless networks,'" *IEEE/ACM Trans. Netw.*, vol. 23, no. 4, pp. 1367–1369, Aug. 2015.

[8] H. Ravishankar and K. K. Patil, "Throughput optimized using evolutionary computing to guarantee QoS in IEEE 802.16 networks," in *Proc. Int. Conf. Smart Technol. Smart Nation (SmartTechCon)*, Bengaluru, India, Aug. 2017, pp. 1602–1606.

[9] V. Singh, D. S. Wadhwa, and M. K. Rai, "Simulative analysis of local area network using WiMAX," in *Proc. Int. Conf. Intell. Circuits Syst. (ICICS)*, Phagwara, India, Apr. 2018, pp. 306–309.

[10] H. V. Prabhu and G. S. Nagaraja, "Adaptive and variable backoff algorithm for IEEE 802.16 to render quality of service," in *Proc. Int. Conf. Commun. Signal Process. (ICCSP)*, Chennai, India, Apr. 2017, pp. 1879–1883.

[11] L. Barletta, F. Borgonovo, and I. Filippini, "The access delay of aloha with exponential back-off strategies," in *Proc. Medit. Ad Hoc Netw. Workshop (Med-Hoc-Net)*, Vilanova i la Geltrú, Spain, Jun. 2016, pp. 1–6.

[12] Y. Xie, H. Qu, and X. Li, "Simulation and analysis on the three-way handshaking time of the coordinated distributed scheduler in IEEE 802.16 mesh mode," in *Proc. 10th Int. Conf. Wireless Commun., Netw. Mobile Comput. (WiCOM)*, Beijing, China, 2014, pp. 419–424.

[13] M. Cao, W. Ma, Q. Zhang, and X. Wang, "Analysis of IEEE 802.16 mesh mode scheduler performance," *IEEE Trans. Wireless Commun.*, vol. 6, no. 4, pp. 1455–1464, Apr. 2007.

[14] P. Khainu and P. Keeratiwintakorn, "An adaptive holdoff exponent approach for coordinated distributed scheduling in WiMAX mesh networks," in *Proc. Int. Symp. Intell. Signal Process. Commun. Syst. (ISPACS)*, Chiang Mai, India, Dec. 2011, pp. 1–5.

[15] S. Yan, "A TDMA MAC scheduling protocol algorithm for wireless mobile ad hoc network and its performance analyses," in *Proc. 5th Int. Conf. Comput. Sci. Netw. Technol. (ICCSNT)*, Changchun, China, Dec. 2016, pp. 471–475.

[16] X. Zhao, L. Lei, and Z. Li, "Modeling and analyzing per-flow saturation throughput for wireless ad hoc networks with directional antennas," in *Proc. Int. Conf. Comput. Technol., Electron. Commun. (ICCTEC)*, Dalian, China, Dec. 2017, pp. 1234–1237.

[17] X. Li, H. Gao, Y. Liang, K. Xiong, and Y. Liu, "Performance modeling and analysis of distributed multi-hop wireless ad hoc networks," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, India, May 2016, pp. 1–6.

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