Research on Resource Efficiency Optimization Model of TDMA-Based Distributed Wireless Ad Hoc Networks

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ABSTRACT

Because of networking flexibility, strong robustness and expansibility, and low cost of operation and maintenance, distributed wireless ad hoc networks are widely used in ultra-density 5th-Generation (5G) networks, Device to Device (D2D) communications and industrial wireless sensor networks. However, compared with the centralized ones, the Time Division Multiple Access (TDMA)-based distributed network lacks centralized coordination by a control center, while its resource scheduling only depends on partial information, and the high receiving failure probability caused by neighbors’ cumulative interference outside the scope of maintenance may reduce the resource efficiency and restrict its usability according to the existing protocols severely. The simulation results show that the transmission failure probability can be up to 20% when maintaining two-hops neighbors in TDMA-based coordinated distributed scheduling. But the research on the cumulative interference outside the scope of maintenance and the optimal neighbor maintenance scope is still unclear at present. In this paper, we establish a resource efficiency model and an interference model of control messages and data messages under different neighbor maintenance by hardcore point process (HCPP) considering cumulative interference, cost of Media Access Control (MAC) layer and channel multiplex. Furtherly, we build an optimization model to maximize the resource efficiency under scheduling delay and receiving success probability constraints, thus we can obtain the optimal scope of maintenance in different network conditions. We conduct extensive theoretical analysis and simulations to evaluate the correctness of models. Simulation results show that the resource efficiency optimization model can provide guidance for optimal protocol parameters design.

INDEX TERMS

Distributed wireless ad hoc networks, cumulative interference, optimal resource efficiency, neighbor maintenance.

I. INTRODUCTION

There are mainly two types of wireless ad hoc networks: centralized wireless ad hoc networks and distributed wireless ad hoc networks. Centralized networks are adopted in the requirements of Quality of Service (QoS) in the field of public cellular networks. However, with the increasing scale of the network and the development of 5G and D2D communications, the scheduling mechanisms of centralized wireless networks will cause a series of problems, such as increasing of the operation cost and signaling consumption, the complexity of setting the center point, and so on [1].

Conversely, the distributed wireless ad hoc networks have advantages of networking flexibility and strong robustness and expansibility. It can reuse frequency resources, reduce signaling consumption and improve performance effectively, since its networking and resource scheduling only rely on partial information within the scope of maintenance, and ignore information outside the scope of maintenance.

Compared with centralized networks, it will cause a high probability of receiving failure caused by cumulative interference outside the maintenance range, harder QoS guarantee and other problems [2]. The simulation results show that the transmission failure probability can be up to 20% when maintaining two-hops neighbors in TDMA-based coordinated distributed scheduling [3]. Unfortunately, the research on the
cumulative interference outside the scope of maintenance and the optimal neighbor maintenance scope is still unclear at present. Furthermore, the transport capacity of a network is given by the product between the data-rate \((b/s)\) and the distance \((m)\) through which the bits can be carried in previous studies \([4]\). Classical methods of communication theory are insufficient to analyze distributed wireless ad hoc networks, because the amount of uncertainty present in large wireless networks far exceeds the amount present in point-to-point systems \([5]\). So, the analysis of interference and resource efficiency to design an optimal maintenance become emphases and difficulties of distributed wireless ad hoc networks.

Currently, typical distributed scheduling mechanisms include competition-based Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), Request To Send/Clear To Send (RTS/CTS) and reservation-based TDMA. CSMA/CA mechanism ensures that there is no interference in the carrier detection range by setting a safe carrier sensing distance and forming a repulsion area \([6]\). In the CSMA/CA mechanism, the effective way to overcome cumulative interference is to optimize the carrier sensing distance, but the safe carrier sensing range will be larger if the node density increases, and extremely large distance will lead to reduction of resource efficiency, while the design of adaptive interception mechanism will be more complex \([7]\), \([8]\). In RTS/CTS mechanism, the RTS frames silence neighbor nodes of the sending node by using the maximum transmission power, and the CTS frames silence all receiving nodes to eliminate collisions. However, there are still some nodes cannot hear these messages, causing strong interference on the receiver nodes. In TDMA-based mechanism, nodes broadcast scheduling messages and maintain scheduling information of all neighbors within two hops. The sending node performs a Mesh Election algorithm to access control slots by scheduling information, and orders the data slots through a three-way handshake process, so it avoids access conflict and uses the spectrum resources more effectively than CSMA/CA mechanism and RTS/CTS mechanism \([9]\). What is more, most of the existing research focuses on single-hop scenarios, and lack of performance analysis model for multi-hop scenarios. Focus on these, we analyze interference management and resource efficiency model based on TDMA-based distributed scheduling protocol to optimize the key protocol parameters such as the scope of neighbor maintenance.

To analyze interference and resource efficiency of distributed networks, it is necessary to establish a practical and tractable interference model. In recent years, stochastic geometric theory, especially the stochastic Poisson Point Process theory (PPP), has been widely used in the interference modeling of distributed wireless ad hoc networks. It can model the randomness of node spatial position distribution and get simple analytical solutions. While in many networks, especially with repulsion function and interference controlling schemes, the PPP is not a suitable model since it only considers that the distribution of nodes is always independent \([10]\). Hard Core Point Process (HCPP), which consider that nodes will be cleaned under a given relevant function, has drawn attention as a practical model for wireless networks. However, there is still little research on interference intensity at the receiving nodes of TDMA-based distributed multi-hop wireless ad hoc networks by HCPP models.

Motivated by this, the novel contribution of this paper is as follow.

- Firstly, we build a resource efficiency model considering the signal-to-interference ratio (SIR), cost of the MAC layer and channel multiplex, and the cost of MAC layer includes forwarding and pseudo-collision consumption. Where the relationships between the signal-to-interference ratio (SIR) and parameters including node density, transmission distance, the scope of maintenance and path loss is described by the intensity of interference of control messages and data messages outside the scope of maintenance using HCPP.

- Secondly, we consult scheduling delay and receiving success probability models in TDMA-based distributed wireless ad hoc networks, and establish an optimization model to maximize the resource efficiency under scheduling delay and receiving success probability constraints. Through the model, we can design an optimal neighbor maintenance.

- Furtherly, We launch extensive theoretical analysis and simulations to evaluate the correctness of models. For example, when the maximum scheduling delay acceptable of the system is 45ms, and the minimum receiving success probability of the system is 95%, the resource efficiency can be maximized when the neighbor maintenance range is designed as a 3-hops neighbor. Both theoretical and numerical results are given and we discover that the models established in this paper accurately quantify the efficiency of resources and can guide the optimal design of the protocol.

The structure of this paper is organized as follows. Section II and III review the related work and system model. The analytical model of resource efficiency is established in Section IV. In section V we describe the model of optimal resource efficiency and the numerical analysis of optimal resource efficiency model under scheduling delay and receiving success probability constraints. Simulation results are presented in section VI. Finally, we draw our conclusions in section VII. For the sake of simplicity, the interference outside the scope of maintenance is referred to as interference in the rest part of this paper.

### II. RELATED WORK

Recent related studies cover the analysis of resource efficiency and time-delay. However, the application of HCPP to analyze multi-hop interference and the research on interference management mechanism and resource efficiency of TDMA-based distributed wireless ad hoc networks are under-explored research problems.
Existing works of resource efficiency of TDMA-based distributed wireless ad hoc networks mostly focus on the overall network capacity, but ignore the cumulative interference outside the scope of maintenance, competition and forwarding characteristics of the multi-hop ad hoc networks. Reference [6] studies the optimal frame length which maximizes the channel utilization ratio. However, the paper focuses on the performance of routing and forwarding protocol, without considering the impact of the scheduling in the MAC layer. Reference [11] analyzes the throughput of TDMA-based distributed scheduling, but it does not consider the forwarding factor in multi-hop networks. Reference [12] constructs an effective throughput model which jointly considers the impacts of forwarding traffic and pseudo-collision traffic, provides an effective reference for the establishment of resource efficiency model in our paper. Unfortunately, there are still few pieces of research on designing scope of maintenance of TDMA-based mechanisms to reduce the interference.

In TDMA-based distributed wireless ad hoc networks, analysis of interference should combine the effect of channel conditions, the distribution of spatial users and the MAC layer scheduling mechanism. Reference [13] uses the K-jump model. This model uses the distance of jump to represent the physical distance between nodes, it can be applied to peer-to-peer communication, but it is not suitable for large-scale distributed network. The stochastic geometry was traditionally used for wireless local area networks without interference. The spatial distribution of randomly located transmitters with ALOHA MAC can be captured by the Poisson point process (PPP) [14]. Different from the traditional PPP in which nodes are independently distributed, HCPP use the concept of repulsion and can precisely describe the effect of interference suppression by scheduling in actual networks. One very popular model that has been extensively studied is the Matérn HCPP. Recently, it is commonly considered as a powerful tool for performance analysis of IEEE 802.11 networks [15], LTE-A cellular networks [16] and heterogeneous networks [17]–[20]. According to the research results in [21], [22], there are two types of HCPP. The type I process is suitable for low node-density, but has an error in the estimation of the number of transmitted nodes when the node density is higher. The type II process can be safely approximated by the corresponding non-homogeneous PPP, whereas the type I process cannot. Reference [23] studies the effects of a guard zone on the throughput of wireless body area networks using a HCPP type II model and [24] proposes a multiuser multiantenna random one-hop cellular network model with the aforementioned minimum distance constraint for adjacent BSs based on HCPP, without considering the effect of the multi-hop interference caused by scope of maintenance. To summarize, most of the existing research based on HCPP model focuses on cellular networks, which scope of maintenance is one hop. There is little research on extending the scope of neighbor maintenance to multi-hop and considering the interference outside the scope. We focuses on the application of HCPP in interference analysis of TDMA-based multi-hop mechanism, which can make up the gap for researches.

III. SYSTEM MODEL
A. TDMA-BASED DISTRIBUTED RESERVATION SCHEDULING MECHANISM

In TDMA-based distributed reservation scheduling mechanism, each MAC frame is divided into control slots and data slots. In Fig.1, each frame has \( C + D \) time slots, where control slots \( (C) \) for transmitting network signaling constitute control sub-frame, while data slots \( (D) \) for transmitting data constitute data sub-frame. Control slots are used to transmit control messages such as network entry message (NENT), network configuration message (NCFG) and distributed scheduling message (DSCH) while data slots are used to transmit users’ traffic.

FIGURE 1. MAC Layer Frame Structure.

In distributed scheduling, nodes of H-hops distance to a node are called its \( H \)-hops neighbors, and all the \( H \)-hops neighbors of a node form a \( H \)-hops neighborhood domain. (As shown in Fig.2, one-hop neighbors of node 1 is node 2, 3, two-hop neighbors are nodes 4,5,6.) In IEEE 802.16, the \( H \) is 2. In IEEE 802.16, all nodes broadcast DSCH to notify their own one-hop neighbors of their scheduling information. By exchanging DSCH, all nodes can coordinate data transmissions in their extended 2-hops neighborhood. The nodes perform resource scheduling based on neighbor maintenance information inside 2-hops. The frequency resources outside the 2-hops can be reused.

FIGURE 2. One-hop neighbors and two-hop neighbors.

In TDMA-based distributed wireless ad hoc networks, the reasonable timesharing resource scheduling strategy can
effectively reduce collisions and delay, improve channel utilization and provide QoS guarantee for users. The scheduling mechanism is different for control messages and data messages. The nodes compete for control messages based on Mesh Election algorithm. After the last successful election, the nodes cannot continue election competition until the nodes hold off for a certain number of control slots. Then the nodes select the competitor from the neighbor and immediately enter the competition process for the next transmission slot, and use pseudo-random algorithm to determine the competition result. If the competition is successful, control messages can be sent at the arrival of the slot, and then the nodes hold off. If the competition is failing, the same method is used to compete for the next control slot. For data messages, the negotiation and reservation mechanism are adapted to realize collision-free transmission. The nodes which need to transmit data, use the three-way handshake process (Request-Grant-Confirm) to negotiate the required slots. Since control messages are transmitted in broadcast form, their adjacent nodes also need to perform avoidance according to the authorization time slots, except for the requesting and authorized nodes. So, it is possible to prevent the interference collision caused by simultaneous transmission.

**B. HCPP MODEL**

Interference management based on TDMA mechanism establishes a certain range of interference-free protection area around the communication nodes. Since node-density and expansion of scale are increasing, the cumulative interference problem will be more and more serious, which will cause transmission failure. While HCPP can closely meet the MAC layer interference avoidance mechanism and describe the distribution of interference nodes more accurately.

With a certain transmitting node as the center, there is no other transmitting node in the H-hops radius of this node, that is, a circular interference free protection area with HR radius is formed around the transmitting node. Where R is the effective distance of the signal transmission.

According to the research in [20], the HCPP type-II model can achieve the almost level of interference intensity with PPP, whereas the type I process cannot. Therefore, we use the type II to analyze the interference intensity. The algorithm steps are as follows.

1) Generate a Poisson process \(\phi_p\) with an average node density of \(\lambda_p\).

2) For each point \(x \in \phi_p\), we add a randomly assigned tag \(m_x \in U[0, 1]\). The tag between points is independent of each other.

3) For each point in circle \(V(x, \delta)\), if the tag of the point is the smallest, we discard all the other points except the smallest one.

Where \(U[0, 1]\) represents a uniform distribution between 0 - 1, the \(\delta\) is the minimum distance, that is, the dilution radius.

The ways of choosing the points and decreasing the density of sending nodes by HCPP can be concluded as followed.

\[
\psi = \{x : x \in \phi_p, m_x < m_y, \forall y \in V(x, \delta) \cap \phi_p\} \tag{1}
\]

where \(x\) represents the point selected in the circle \(V(x, \delta)\).

According to this method, we can get all the reserved points. The distribution model formed by all the remaining points is the HCPP type-II model. As shown in Fig.3, within the distance \(x\) of the node labelled with the value of 0.1, which is the minimum. So, it is reserved in the HCPP, meanwhile the node labelled 0.2 is cleared. Similarly, HCPP preserves nodes labelled 0.3 and 0.5, and clears nodes with 0.4 and 0.6.

We assume the node density of a distributed wireless ad hoc network follows the PPP with the mean value of \(\lambda_p\). Practically, the communication nodes use interference management mechanism to clear the interference nodes within a certain range, and the remained interference nodes obey HCPP.

The density of the remained nodes is given by

\[
\lambda_H = \lambda_p \int_0^1 e^{-\lambda_p \pi x^2} dx = \frac{1 - e^{-\lambda_p \pi \delta^2}}{\pi \delta^2} \tag{2}
\]

Denote \(k(s)\) is the probability that two nodes apart from \(s\) can exist simultaneously. To reflect the interaction relation of two nodes, [25] mentions the spatial correlation function \(g(s)\) between every two nodes is

\[
g(s) = \frac{\lambda_H^2 k(s)}{\lambda_P^2} \tag{3}
\]

We suppose that the sending node is in the origin \(o\), \(s\) denotes the distance between two transmission nodes and \(\varphi\) denotes the direction of the receiving node. Then the interference intensity at the receiving node is derived from

\[
E(I) = \lambda_H \int_0^\infty \int_0^{2\pi} l(s)g(s)sdxd\varphi \tag{4}
\]

where \(l(s)\) represents the path loss model. If we only consider the path loss, then \(l(s) = s^{-\alpha}\), and \(\alpha\) is the path loss index.

![Diagram of HCPP model.](image-url)
IV. RESOURCE EFFICIENCY MODEL

Existing literature about resource efficiency models mostly focus on the overall network capacity, but ignore the cumulative interference outside the scope of maintenance, competition and forwarding characteristics of the ad hoc networks. So, in this section, we establish the resource efficiency model of distributed wireless ad hoc networks to accurately quantify the efficiency of resources by considering the factors such as the cumulative interference, forwarding and pseudo-collision consumption of MAC layer and channel multiplexing and so on.

We can get the resource efficiency of the distributed wireless ad hoc networks. The Eq.5 for resource efficiency is at the bottom of this page.

In the resource efficiency model, the denominator is all resources within a frame, including control messages resources and data messages resources, and the numerator is a resource for transmitting valid data within a frame. We can see that the resource efficiency is affected by the number of control slots and data slots, the node density of networks, the number of data sources, and the scope of neighbor maintenance.

The capacity model of data messages and control messages and forwarding and pseudo collision traffic model are described in detail below. Where the capacity model of data messages and control messages using HCPP model.

A. THE CAPACITY MODEL OF CONTROL MESSAGES

In this part, we use HCPP model to value of the SIR of control messages in election process, then calculate the capacity of control messages by the Shannon capacity and the interference intensity.

The nodes compete for control messages based on Mesh Election algorithm. In the election mechanism, nodes maintain the scheduling information of its H-hops neighbors. The nodes that want to access the channel compete with other nodes in the H-hops range. Only one node is selected in each slot, which occupies the channel to broadcast information in the winning time slot. And there will be a circle cleaning area slot, which occupies the channel to broadcast information in and the dilution radius is

\[ \lambda = \frac{\text{effective transmission radius of the control messages}}{\text{channel}} \]

That is, \( \lambda = HR \). As shown in Fig.4, the distribution of the interfering nodes is fully consistent with the HCPP model, where the interference node density \( \lambda_{\text{con}} = \frac{\lambda}{\pi R^2} \).

We can get the interference density \( \lambda_{\text{con}} \) of control messages in the election mechanism.

\[ \lambda_{\text{con}} = \lambda \int_0^1 e^{-\lambda_p \pi H^2 R^2} dx = \frac{1 - e^{-\lambda_p \pi H^2 R^2}}{\pi H^2 R^2} \]

We can see that the interference node density \( \lambda_{\text{con}} \) is not only affected by the density of networks nodes but also related to the number of neighbor hops maintained by the nodes under the election mechanism. With the increase of node density, the \( \lambda_{\text{con}} \) begins to decrease. When the node density increases to a certain extent, \( \lambda_{\text{con}} \) remains unchanged.

Using \( s \) to represent the distance between two nodes in HCPP with the density \( \lambda_p \), we can get the joint area size \( V(s)_{\text{con}} \), whose centers are separated by \( s \) and the radius is \( HR \).

\[ V(s)_{\text{con}} = \begin{cases} 0, & s < HR \\ 2\pi H^2 R^2 - 2H^2 R^2 \arccos\left(\frac{s}{2HR}\right), & HR \leq s \leq 2HR \\ 2\pi H^2 R^2 - \frac{s^2}{4} - s HR, & s > 2HR \end{cases} \]

After diluting the density of initial networks nodes by the election algorithm, the probability that the nodes with the distance \( s \) from the receiving node \( k(s)_{\text{con}} \) can be preserved as

\[ k(s)_{\text{con}} = \frac{2V(s)_{\text{con}}(1 - e^{-\lambda_p H^2 R^2}) - 2\pi H^2 R^2(1 - e^{-\lambda_p V(s)_{\text{con}}})}{\lambda_p \pi H^2 R^2 V(s)_{\text{con}}[V(s)_{\text{con}} - \pi H^2 R^2]} \]

And

\[ g(s)_{\text{con}} = \begin{cases} 0, & s < HR \\ \frac{\lambda_p^2}{\lambda_{\text{con}}^2} \cdot k(s)_{\text{con}}, & HR \leq s \leq 2HR \\ 1, & s > 2HR \end{cases} \]

Therefore, we can get the value of the SIR at the receiver.

\[ E(\text{SIR})_{\text{con}} = \frac{d^{-\alpha}}{2\pi \lambda_{\text{con}} \int_{HR}^{2HR} \int_0^\infty (s) (s)_{\text{con}} ds ds + 2\pi \lambda_{\text{con}} \int_{HR}^{2HR} \int_0^\infty (s) ds ds} \]

\[ \text{capacity of control messages and data messages} \]

\[ \eta = \frac{\text{multiplexing coefficient} \times (\text{capacity of datamessages} - \text{forwarding traffic} - \text{pseudo collision traffic})}{\text{capacity of control messages}} \]
where $d$ denotes the distance between two transmission nodes, $d \leq R$.

We can see that the larger the value of path loss index and the smaller the value of transmission distance is, the larger the value of SIR is. Besides, the SIR of control messages in election mechanism is not only affected by the node density of networks and path loss but also related to the number of neighbor hops maintained by the nodes under the election mechanism.

So, the capacity of control messages $R_C$ is

$$R_C = W \cdot \log_2(1 + E(\text{SIR})_{\text{con}}) \quad (11)$$

where $W$ is bandwidth of this system.

B. THE CAPACITY MODEL OF DATA MESSAGES

In this part, we use HCPP model to value of the SIR of data messages in three-way handshake process, then calculate the capacity of data messages by the Shannon capacity and the interference intensity.

The scheduling of data messages is based on the three-way handshake mechanism of the message exchanging of DSCH. On the sending node and receiving node, there will be two circular noninterference area whose radius is $R$.

As shown in Fig.5, we assume that the sending node $x_1$ is the polar origin $o$, the corresponding receiving node is in the 0 degree direction of $x_1$, and the distance between them is $d$. We use $(s, \beta, \varphi)$ to indicate the position of another pair of communication (interference communication) in the network. Where $s$ denotes the distance between two transmission nodes $x_1$ and $x_2$, and the interference transmission node $x_2$ is located in the $\beta$ direction of the point $o$ and the interference reception node is in the direction $\varphi$ of the interference transmission node. To simplify calculations, we suppose that the distance between all the communication pairs in the network is $d$, then the interference area of the two communication pairs is only a function of $(s, \beta, \varphi)$.

The union area $V(d)_{\text{data}}$ of two circles is the non-interference area set by the handshake mechanism.

$$V(d)_{\text{data}} = 2(\pi - \arccos \frac{d}{2R})R^2 + dR \sin(\arccos \frac{d}{2R}) \quad (12)$$

With the help of the density formula of HCPP model, we can get the density of interference nodes in a handshake mechanism when taking $V(d)_{\text{data}}$ into the formula

$$\lambda_H = \lambda_p \int_0^1 e^{-\lambda_p V(d)_{\text{data}}} \ dx = \frac{1 - e^{-\lambda_p V(d)_{\text{data}}}}{V(d)_{\text{data}}} \quad (13)$$

Next, if the distance between $x_1$ and $x_2$ is less than $HR$, or the distance between $x_2$ and the receiving node of $x_1$ is less than $HR$, then the two communication pairs cannot coexist at the same time. Similarly, if the receiving node of $x_2$ is in the interference clearing region of $x_1$, the probability of coexistence of the two communications pairs is also 0. In addition to the above, the probability of the two communication pairs is calculated as

$$k(s, \beta, \varphi) = \frac{V(s)_{\text{con}} - V(s)_{\text{con}} e^{-\lambda_p V(d)_{\text{data}}} - V(d)_{\text{data}} + V(d)_{\text{data}} e^{-\lambda_p V(s)_{\text{con}}}}{\lambda_p^2 [V(s)_{\text{con}} - V(d)_{\text{data}}] V(d)_{\text{data}} V(s)_{\text{con}}} \quad (14)$$

The correlation function $g(t)$ of the two communication pairs is represented as Eq.15, which is at the bottom of the next page.

where $\epsilon = \varphi - \beta + \arccos \frac{s - d \cos \beta}{\sqrt{s^2 - 2sd \cos \beta + d^2}}$.

According to the definition of interference intensity, we can get the value of the SIR in the three-way handshake process as Eq.16, which is at the bottom of the next page.

Like SIR of control messages in election mechanism, the SIR of data messages in three-way handshake mechanism is also affected by the node density of networks and the number of neighbor hops maintained by the nodes.

So, the capacity of data messages $R_D$ is

$$R_D = W \cdot \log_2(1 + E(\text{SIR})_{\text{data}}) \quad (17)$$

C. FORWARDING AND PSEUDO COLLISION TRAFFIC MODEL

In a multi-hop networks, each node should guarantee timely transmission of its own traffic as well as forwarding certain volume for its neighbors. Forwarding is one of the most typical features of ad hoc networks which can make better use of the idle bandwidth and increase throughput. However, forwarding too much will cause congestion and reduce the effective throughput. In this paper, we quote [12] and suppose that the total number of nodes in the network is $N$, then the forwarding traffic $FLOW$ in time $t$ can be obtained.

$$FLOW = \frac{[\ln N - \ln(\pi R^2 \lambda_p)]}{(N - 1) \ln(\pi R^2 \lambda_p)} \eta' t \quad (18)$$

where $\eta'$ is resource efficiency without considering multiplexing coefficient.
Under the assumptions of the distributed scheduling mechanism, the nodes are not allowed to transmit while their one-hop neighbors receive to avoid collisions resulting in transmission blank within a certain time interval. However, this transmission blank is not caused by actual collisions. Pseudo collision slots refer to the time interval in which transmission blank within a certain time interval. However, one-hop neighbors receive to avoid collisions resulting in

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The resource efficiency model can be seen, the resource efficiency is mainly affected by node density and the scope of neighbor maintenance. To maximize the resource efficiency and guarantee the QoS requirements, we take the receiving success probability and scheduling delay as constraints, and combine the interference intensity and resource efficiency model to express the optimal resource efficiency model.

### A. OPTIMAL RESOURCE EFFICIENCY MODEL

Based on the above factors such as interference intensity, forwarding and pseudo collision consumption, the optimal resource efficiency model is expressed as

\[
\begin{align*}
\text{max} : & \eta \\
\text{s.t.} : & T_{sch} \leq T \\
& P_{RCV} \leq P_{\text{control}} \\
& P_{RCV} \leq P_{\text{data}}
\end{align*}
\]

V. NUMERICAL ANALYSIS OF OPTIMAL RESOURCE EFFICIENCY MODEL UNDER SCHEDULING DELAY AND RECEIVING SUCCESS PROBABILITY CONSTRAINTS

where \( \eta \) is the resource efficiency; \( T_{sch} \) is the scheduling delay; \( T \) is the maximum scheduling delay acceptable of the system; \( P_{\text{control}} \) and \( P_{\text{data}} \) are the success probability of the reception of control messages and data messages in the election process and the three-way handshake process; \( P_{RCV} \) is the minimum receiving success probability acceptable of the system.

The receiving success probability model, the scheduling delay model are described in detail below.

### B. RECEIVING SUCCESS PROBABILITY MODEL

In Additive White Gaussian Noise (AWGN) channel, the needed bit error rate (BER) of different modulation models are shown in TABLE.1.

We use forward error correcting codes (FEC) to simplify the model. The probability of successful reception \( P_{RCV} \) is

Based on the above factors such as interference intensity, forwarding and pseudo collision consumption, the optimal resource efficiency model is expressed as

\[
\begin{align*}
\text{max} : & \eta \\
\text{s.t.} : & T_{sch} \leq T \\
& P_{RCV} \leq P_{\text{control}} \\
& P_{RCV} \leq P_{\text{data}}
\end{align*}
\]
given by
\[
P_{RCV} = \left\{ \begin{array}{ll}
\frac{1}{2} \varepsilon_{fi}(\sqrt{SPR}) & n - k \geq \frac{1}{\log_2\left(\sum_{m=0}^{m=n} C_n^m p^{n-m}(1-p)^m\right)} \\
0 & \text{otherwise}
\end{array} \right. \tag{24}
\]
where \( n \) is a set of code words and \( k \) is the number of information codes in the linear block code \((n,k)\); \( m \) is error correction capability; \( F \) is the number of code words contained in each packet; \( g \) is the maximum number of packets.

C. SCHEDULING DELAY MODEL

If the node maintains a neighbor within the range of \( H \)-hops, the node selects competitors from the neighbor nodes to determine the contention set (including the node itself) when competing for a control slot \([12]\).

The average delay \( E[T_H] \) of the whole three-way process is calculated as
\[
E[T_H] = 3 \left(\frac{2^{exp+bas} (2^{exp+bas} + 1)p}{2(1 - p)^{2^{exp+bas}}}ight) - \int_0^1 \frac{(1 - x)^{exp+bas - 1}}{1 - x} dx + \frac{1 - p}{p} \tag{25}
\]
where the probability of successful competition \( P \) is given by
\[
\frac{1}{p} = (\pi H^2 + \lambda_p - 1) \frac{2^{exp} + 1/p}{2^{exp+bas} + 1/p} + 1 \tag{26}
\]
where \( exp \) is the dynamic back off exponent, \( bas \) denotes the fixed back off exponent.

The time \( t_C \) for the control slot and \( t_D \) for the data slot are as follows
\[
t_C = \frac{L_C}{R_C} \times C \quad t_D = \frac{L_D}{R_D} \times D \tag{27}
\]
where \( L_C \) and \( L_D \) are the amount of data transferred in each control slot and data slot.

The time taken for each frame \( T_F \) is given by
\[
T_F = \frac{L_C}{R_C} \times C + \frac{L_D}{R_D} \times D \tag{28}
\]
Thus, we can get the scheduling delay \( T_{scheduling} \) in seconds from
\[
T_{scheduling} = \left\lceil \frac{E(T_H)}{C} \right\rceil \cdot T_F + \left\lceil \frac{E(T_H)}{C} - \left\lceil \frac{E(T_H)}{C} \right\rceil \cdot C \right\rceil \cdot t_C \tag{29}
\]
where \( \lceil \cdot \rceil \) means rounding downwards to the nearest integer.

D. NUMERICAL ANALYSIS OF OPTIMAL RESOURCE EFFICIENCY MODEL

As can be seen from the various models below, the optimization problem is a convex optimization problem, which can be solved using KKT conditions. So, to maximize the efficiency of the resource with the constraints of scheduling delay and acceptance success, we use Kuhn-Tucker model to analyze optimal resource efficiency model. Through numerical analysis, the closed solution of neighbor maintenance range and node density is obtained, which can provide reference for further optimization of protocol design.

According to the K-T model, the optimal resource efficiency equation is simplified as follows
\[
\begin{align*}
\frac{\partial (-\eta)}{\partial H} + u_1 \frac{\partial (T_{scheduling} - T)}{\partial H} + u_2 \frac{\partial (P_{RCV} - P_{control})}{\partial H} = 0 \\
\frac{\partial (-\eta)}{\partial \lambda_p} + u_1 \frac{\partial (T_{scheduling} - T)}{\partial \lambda_p} + u_2 \frac{\partial (P_{RCV} - P_{control})}{\partial \lambda_p} = 0 \\
u_1, u_2, u_3 \geq 0 \\
u_1(T_{scheduling} - T) = 0 \\
u_2(P_{RCV} - P_{control}) = 0 \\
u_3(P_{RCV} - P_{data}) = 0
\end{align*} \tag{30}
\]

According to the maximum scheduling delay and minimum receiving success probability acceptable for the system, we can get the optimal neighbor maintenance range, which are shown in TABLE.2

| Scheduling delay (ms) | Receiving success probability | Optimal neighbor maintenance range (hop) | Optimal node density (nodes/km²) |
|-----------------------|------------------------------|----------------------------------------|-------------------------------|
| 25                    | 70%                          | 2                                      | 5.355                         |
| 30                    | 75%                          | 2                                      | 5.176                         |
| 35                    | 80%                          | 2                                      | 5.024                         |
| 40                    | 90%                          | 3                                      | 7.469                         |
| 45                    | 95%                          | 3                                      | 7.578                         |

Through the TABLE.2, we can see that in a large-scale network covering more than 2-hops, in order to make the system resources more efficient, if the system delay requirements more stringent when the bandwidth is fixed, it can only maintain 2-hops neighbors, however, the receiving success probability is low. When the system requests a higher success rate (80% or more), the optimal neighbor maintenance range increased to 3-hops, then the original election mechanism and the three-handshake mechanism in IEEE 802.16 are no longer applicable, and the scheduling mechanism in the protocol should be re-designed. In practical application, to optimize resource utilization, the appropriate node density can be set by power control or other measures.
VI. SIMULATION RESULTS

In this section, we simulate the relationship between key parameters such as node density and the neighborhood maintenance and resource efficiency by Network Simulator version 2 (NS2).

A. SIMULATION SCENE AND VALUE OF PARAMETERS

We build a communication scenario and set nodes with random position using tcl language on NS2 platform. In $10km \times 10km$ area, we set up randomly distributed nodes. The part of network topology diagram when $\lambda_p = 10 \text{ nodes/km}^2$ is shown in Fig.6.

The value of parameters in this paper is shown in TABLE.3.

| Parameters | Meaning | Value |
|------------|---------|-------|
| $H$        | hops    | 2.3, 4 |
| $N$        | number of nodes | $\pi (H+1)^2 R^2 \lambda_p$ |
| $\alpha$   | path loss exponent | 3 |
| $\lambda_p$| network node density | 1-100(node/m$^2$) |
| $R$        | effective transmission radius of DSCH | – |
| $d$        | sending-to-receiving node distance | $d < R$ |
| $\beta$    | direction of the other sending node | $[0, 2\pi]$ |
| $\varphi$  | direction of sending-to-receiving node | $[0, 2\pi]$ |
| $\gamma$   | multiplexing coefficient | – |
| $exp$      | dynamic back off exponent | 1 |
| $bas$      | fixed back off exponent | 4 |
| $C + D$    | the number of slots | 32 |

The value of parameters in this paper is shown in TABLE.3.

B. SIR OF CONTROL MESSAGES AND DATA MESSAGES

The theoretical and simulation results of SIR of control messages and data messages in election mechanism and three-way handshake mechanism are shown in Fig.7 and Fig.8.

Fig.7 and Fig.8 show the receiver SIR changes with the node density of control messages and data messages in election mechanism and three-way handshake mechanism. The path loss index is set to 3. Take $H = 2$, $d = 250$, $\lambda_p > 10 \text{ nodes/km}^2$ as an example. The received SIR has dropped to about 11dB. After expanding the scope of the neighborhood to 3-hops, SIR can be increased to more than 13 dB and 16 dB.

Fig.7 and Fig.8 show that the receiver SIR decreases as the density of nodes increases, which is due to the increase of node density, the decrease of scope of maintenance ($H$) and the increase of distance between sending node and receiving node which leads to the increase of interference node density. More importantly, When the node density $\lambda_p > 10 \text{ nodes/km}^2$, the effect of node density on the SIR is negligible. On this condition, the important factors that affect the SIR are channel fading exponent and neighbor maintenance hops. The channel condition is uncontrollable, so it is an effective way to optimize the number of hops.

C. RECEIVING SUCCESS PROBABILITY

To fully reflect the influence of neighbor maintenance range on network performance, we assume that the system adopts 16QAM and 64QAM modulation, and the path loss index is 3, the sending-to-receiving node distance is 250Km. The
theoretical results and simulation results of the receiving success probability are shown in Fig.9.

Fig.9 reveals that the receiving success probability decreases as the density of nodes increases, which is due to the decrease of SIR. And the maximum receiving success probability is less than 80% when the neighbor maintenance range is 2-hops, and the receiving success probability decreases rapidly with the increase of node density. When the neighbor maintenance range is 3-hops or more, the system receives more than 90% success rate, which can meet the transmission requirements of high-quality service. Also, because the HCPP nodes density is quickly limited, transmission success probability tends to be fixed.

D. SCHEDULING DELAY

According to the IEEE 802.16 protocol, we suppose that each control slot (where we refer to DSCH message) carries a set of election parameters (3 bytes) and a set of scheduling information (5 bytes) for each neighbor. So, the amount of data transferred in each control slot $L_C = 34 + 8N$ bytes, and the amount of data transferred in each data slot $L_d$ is 414 bytes. The fixed back off exponent is set to 4, the dynamic back-off exponent is set to 1. We can get the theoretical results and simulation results of scheduling delay (unit: control slot number / secs) shown in Fig.10 and Fig.11.

We can see that control slots which needed to complete the resource scheduling process increase along with increasing neighbor maintenance area and node density, so that the scheduling delay is smaller when the node density is small. Besides, the capacity of control slots and data slots increases as the neighbor maintenance area, because the increasing neighbor maintenance makes each frame time shorter. As a result, the scheduling delay is smaller when the node density is large and node density is small. However, the scheduling delay is larger when the neighbor maintenance is large and node density is large, because the increasing of control slots needed to maintain more neighbor information is greater than the advantage of short frames.

E. RESOURCE EFFICIENCY

Fig.12 compares the theoretical and simulation results of resource efficiency. We assume that the path loss index is 3 and fixed back off exponent is 4. The points on the graph represent the theoretical, the lines represent simulation results.

Fig.12 reveals that resource efficiency increased first and decreased when the node density increased and the theoretical analysis is basically consistent with the simulation. The reason for this is that as the node density increased, more
and more nodes bear forwarding task, so the transmitting capacity increased. However, as the node density continued to increase, forwarding consumption and pseudo-collision consumption continued to increase, control slot consumption got too excessive to increase resource efficiency continuously. Besides, forwarding consumption and pseudo-collision consumption increased along with neighbor maintenance, control messages have to carry more scheduling information, which leads to a reduced resource efficiency.

F. OPTIMAL RESOURCE EFFICIENCY

Scheduling delay, receiving success probability, resource efficiency of different neighbor maintenance and node density are analyzed jointly. In order to display the data better, we only show several important points. Simulation result of optimal resource efficiency model is shown in Fig.13.

From Fig.13 we can see that the optimal resource efficiency could be as high as 0.8849 when the maximum scheduling delay is 23.38 ms and the minimum receiving success probability is 78.58%. In this condition, the neighbor maintenance is 2-hops, node density is 5 nodes/km². The optimal resource efficiency could be as high as 0.7592 when the maximum scheduling delay is 40 ms and the minimum receiving success probability is almost 100%. In this condition, the neighbor maintenance is 3-hops, node density is 7 nodes/km².

From the above simulation results, we can conclude that neighbor maintenance needs to be extended to ensure a higher receiving success probability, however, which may cause the increase of scheduling delay. Therefore, neighbor maintenance should be specified according to the actual demand.

Moreover, the simulation results are consistent with the theoretical analysis result in the constraint meeting different receiving success probability and scheduling delay. The optimal neighbor maintenance and node density of different parameters could be set with the method in this paper, the error of simulation analysis could be reduced, and strong support could be provided for further optimizing the protocol design.

VII. CONCLUSION

The TDMA-based distributed network lacks centralized coordination by a control center, while its resource scheduling only relies on partial information, and the high receiving failure probability caused by neighbors’ cumulative interference outside the scope of maintenance may reduce the resource efficiency and restrict its usability under the existing protocols severely. The simulation results show that the transmission failure probability can be up to 20% when maintaining 2-hops neighbors in TDMA-based coordinated distributed scheduling. In this paper, we establish a resource efficiency optimization model of distributed ad hoc networks by HCPP, taking the neighbors’ cumulative interference, channel multiplexing, forwarding and pseudo collision into consideration, to research the cumulative interference outside the scope of maintenance and obtain the optimal neighbor maintenance under different scheduling delay and success probability constraints by theoretical analysis and simulation. Through theoretical and simulation results by NS2 we can prove that the model accurately reflects the influence of network’s key parameters such as the MAC layer scope of maintenance, node density and other effects, so that we can get the optimal neighbor maintenance in actual conditions by this model. It lays the foundation for upgrading the system resource efficiency and optimizing the protocol design. In the future study, we will consider more complex channel conditions, mobile scenarios and other unstable factors to perfect model and improve the resource efficiency of the system.

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