A Joint Optimization Method for Scheduling and Random Access Based on the Idea of Particle-Based Access in IEEE 802.11ax

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Abstract. At present, there are some problems in the mechnism of guarantee for the delay of uplink service in IEEE 802.11, 1) Many studies have optimized the expectation of delay of random access, but cannot privide deterministic guarantee of delay. 2) Scheduling access can effiectively provides guarantee for the performance of the delay of service, but there are some very urgent packets that cannot tolerate the waiting time required by scheduling. 3) There are few studies that consider optimal the delay of both scheduling and random access. To solve these problems, this paper proposes a joint optimization method of scheduling and random access, based on the idea of minimum access bandwidth in the theory of particle access and the corresponding access strategy: EDF (Early Deadline First). As a result, the packets created by scheduling users are in the minimum access bandwidth range at each time, and the idle time-frequency resources are distributed as evenly as possible in time. Therefore, the probability of collision between random access users and the resulting long waiting time can be reduced. The simulation results show that under the condition of moderate total traffic, the joint optimization method proposed in this paper can significantly reduce the access delay of random users on the premise of ensuring the delay requirements of scheduling users. The research result of this paper provides a new idea for further optimizing the delay of the scheduling and random users.

Keywords: Particle access · IEEE 802.11ax · Joint optimization of scheduling and random access · Guarantee of delay

1 Introduce

In recent years, with the rapid development of intelligent applications, the number of nodes in the network continues to expand, and users are more and more sensitive to the delay of wireless communication. However, the traditional access

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method of WiFi is CSMA/CA, which will cause a lot of collisions when there are a large number of nodes or a large amount of traffic. It will make the delay impossible to guarantee. Therefore, it is necessary to design a MAC protocol that can guarantee the requirement of delay. The research on service delay is mainly divided into two aspects, namely, optimizing random access and optimizing scheduling access. Both scheduling and random access, when scheduling access, AP allocates RU to STAs by sending Trigger Frame (TF); when random access, STA performs random access through Uplink-OFDMA Random Access (UORA). The main content of the research on optimizing random access is to optimize the delay through reservation, adaptive adjustment of parameters and other methods on the basis of the traditional CSMA/CA of IEEE 802.11. In [1], a Probabilistic Complementary Transmission Scheme (PCTS) is proposed to allow nodes to perform backoff retransmission with a certain probability after transmission failure to alleviate the retransmission delay and reduce unnecessary backoff window expansion. Reference [2] proposes a Multi-dimensional Busy Tone Arbitration (MBTA) mechanism, the arbitration phase is added before the node sends in UORA, which greatly reduces the probability of collision. References [3,4] use NOMA and beamforming mechanisms respectively to achieve simultaneous transmission by multiple STAs on the same RU to reduce collisions. However, the optimization of random access is still full of uncertainty and cannot provide a deterministic guarantee for delay.

The core idea of optimal scheduling access is to use AP to reasonably schedule the associated nodes to avoid collisions and meet the requirements of QoS for data packets. References [5,6] make adjustments on the basis of traditional polling to achieve guarantee of delay, Reference [5] analyzed the uplink delay performance of HCCA, and proposed a method to adaptively adjust the time of TXOP and other stages to ensure the delay. Reference [6] proposes that before data polling, an additional round of information transmission is added to report whether each node has packets to send, and nodes without packets will be skipped during data polling. Reference [7] also adopts the idea of separation of contral information and data transmission, based on the BSR of IEEE 802.11ax, it designs a buffer reporting technology that transmits information and data in two segments. Cooperating with the energy-saving mechanism it can improve efficiency. Reference [8] proposed a fair scheduling algorithm based on the Hungarian algorithm to solve the resource allocation problem of various real-time services in the context of LTE. Reference [9] uses the LTE scheduler to adapt to IEEE 802.11ax and uses the Hungarian algorithm to perform a thorough search with the utility function to get the best RU configuration. Optimized scheduling access can effectively guarantee the delay of general services, however some services' delay requirements are very strict, and the delay brought by scheduling cannot be tolerated, so it is more suitable to use random access to shorten the delay of access.

In the actual scenario, random access and scheduling access must exist at the same time. So these two aspects need to be considered at the same time when designing the MAC protocol for the guarantee of delay. References [10] and [2] research from the perspective of user selection of sending methods. Reference [10] studies the optimal distribution ratio of nodes choosing random access and scheduling access in the system to maximize the total throughput. Reference [2] found that random access is more suitable for short frames, and scheduled access is more suitable for long frames, so the optimal frame duration boundary can be calculated, and the DAMS algorithm is then proposed to let the AP estimate the optimal boundary, and send it to STAs to help select optimal method of access. References [11] studies from the perspective of AP scheduling, it proposes the concept of access capacity entropy, and designs a greedy algorithm Hybrid Access Strategy (HAS), which allocates RU to the user with the largest capacity entropy, However, it only considers throughput maximization and does not consider the guarantee of delay.

Based on the idea of particle access, this paper granulates the uplink service flow into information particles. and proposed a scheduling algorithm based on EDF. It can minimize the access bandwidth of the scheduled users and reduce the random access delay at the same time, and it is called the joint optimization algorithm of scheduling and random access. Then, with the OFDMA technology of IEEE 802.11ax, TF is used to complete the scheduling of subsequent T ms time-frequency resources. The joint optimization algorithm proposed in this paper minimizes the peak access bandwidth under the condition of meeting the requirements of delay for the scheduling user. In this way, more sufficient bandwidth resources are provided to random access packets at each time, so as to meet the requirements of delay for two types of access services (scheduling access and random access) to the limit.

2 Main Idea

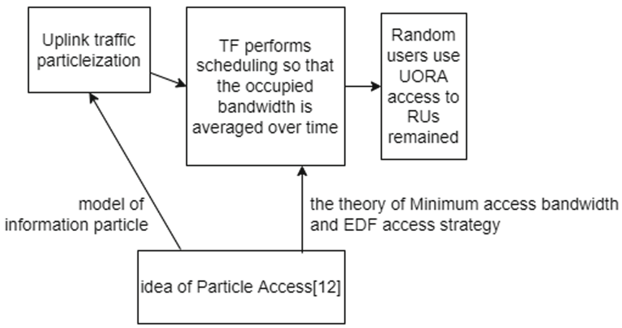


Fig. 1. Schematic diagram of the core idea of a joint optimization method for scheduling and random access based on the idea of particle access based on IEEE 802.11ax

As shown in Fig. 1, the core idea of this paper is based on the idea of particle access, including the flow model based on the information particle, the minimum bandwidth of particle access and its corresponding EDF access strategy. The core idea of this paper can be divided into the following parts:

1. Apply the model of particle access to granulate the uplink service flow into information particles. The end-to-end service flow can be modeled as a group of information particles, in which each information particle is a packet with the attributes of carrying information, creation time and deadline.
2. AP uses the TF to schedule the time-frequency space in the Tms after that, and uses the EDF strategy that can achieve the minimum access bandwidth with the idea of patticle access, so that the bandwidth occupied by the scheduling users is averaged as much as possible in time. Thus, this strategy reserves as much bandwidth resources as possible for random users to compete for access at each time.
3. The random user arrives randomly in the time domain and uses UORA for access [13], that is, the random user generates a random integer within the backoff window. If the positive number is less than the number of idle RUs, it randomly selects a RU for access. Else, the number of idle RUs will be subtracted from the backoff value. If two random users choose the same RU at the same time, it means a collision occuring, the backoff window of both nodes need to be doubled, and the random backoff value is regenerated, and the backoff starts.

3 Introduction to the Theory of Particle Access

In this section, the definitions of information particles, the group of information particles and their attrubutes are given. The sorting operation in the group of information particles is given. The reachable access bandwidth and the minimum reachable access bandwidth are defined. And a theorem proved that EDF is an access transmission strategy that can achieve the minimum accessible access bandwidth is given (the specific proof analysis can be found in Reference [12]).

Definition 1. *Information Particle: Information blocks to be transmitted with specific basic properties (including: carrying capacity I_i, initial time $t_{b,i}$, deadline $t_{e,i}$, etc.) are called information particles,which are used $n_i$to identify. The following are its main attributes: Its effective survival interval is $D_i = [t_{b,i}, t_{e,i}]$(this paper only considers the particles that have arrived, that is, $t_{b,i} = 0$), The length of time covered T_{D_i} is the effective life span of the particle, that is $T_{D_i} = t_{e,i} - t_{b,i}$. The instantaneous transmission rate of the information particle at time t is recorded as $r_i(t)$, If n_i completes transmission within time interval D_i, it is called effiective transmission.*

Definition 2. *the Group of Information Particles: A non empty set containing $N(\geq 1)$meaningful information particles, recorded as Q. Its carrying capacity is the sum of the carrying capacity of all information particles contained,that is $I_Q = \sum_{i \in Q} I_i$. Effective survival space D_Q of Q is the union of the effective survival intervals of all its information particles, that is $D_Q = \bigcup_{i \in Q} D_i$, and the total length of time covered T_{D_Q} is the effective survival span of Q.*

Definition 3. *Ascending sort operation $Op_{Inc}(Q)$ to the group of information particles Q: As given group of information particles Q, sort the information particles from small to large according to the their deadline, and give the ith information particle a serial number of "i", (its deadline is $t_{e,i}$)*

Definition 4. *Reachable Access Bandwidth $B_{re,Q}$ of the Information Particles Q: If there is a transmission strategy that can make all information particles in Qtransmit effectively, and the total instantaneous transmission rate meets $\sum_{i \in Q} r_i(t) \leq B_{re,Q}, (B_{re,Q} > 0, t \in D_Q)$, Then the access bandwidth $B_{re,Q}$ is reachable for Q.*

Definition 5. *Minimun Reachable Bandwidth $B_{re,Q}^{min}$ of the Group of Information Particles Q: the minimum value among all reachable access bandwidths within the effective survival space D_Q of the group of information particles Q.*

Theorem 1. *As for given group of information particles Q, using EDF strategy can achieve effective transmission under the minimum access bandwidth.*

This theorem gives the requirements of minimum bandwidth to send the entire group of information particles effectively, and the EDF strategy just meet all requirements, that is, it proves that EDF strategy can effectively send the whole group of information particles under the minimum reachable access bandwidth (refer to [12] Lemma 2 for a detail proof).

Lemma 1. *In the case of adopting the EDF transmission strategy, as the information particles are transmitted, the required minimum reachable access bandwidth will decrease or remain unchanged.*

This lemma gives the variation of the minimum reachable access bandwidth of a given group of information particles under the EDF transmission strategy. According to this lemma, this paper designs a scheduling algorithm to maintain the bandwidth occupied by information particles with the minimum access bandwidth at every moment. (refer to [12] Corollary 5 of Theorem 4 for a detail proof)

4 Joint Optimization Method of Scheduling and Random Access Based on the Idea of Particle Access

In this section, an access method based on the idea of particle, which is called the joint optimization algorithm of scheduling and random access. It realizes that the bandwidth occupied by the group of information particles of scheduling usrs is down to minimum access bandwidth at every time. The detailed algorithm flow of this method will be introduced below.

As shown in Fig. 2, the AP accesses the channel and enters the preparation phase. Firstly, AP obtains the transmission buffer information of the associated STAs through the technology of BSR, and obtains the deadline and carrying information of each packet which is ready to send in each STA. Then AP maps

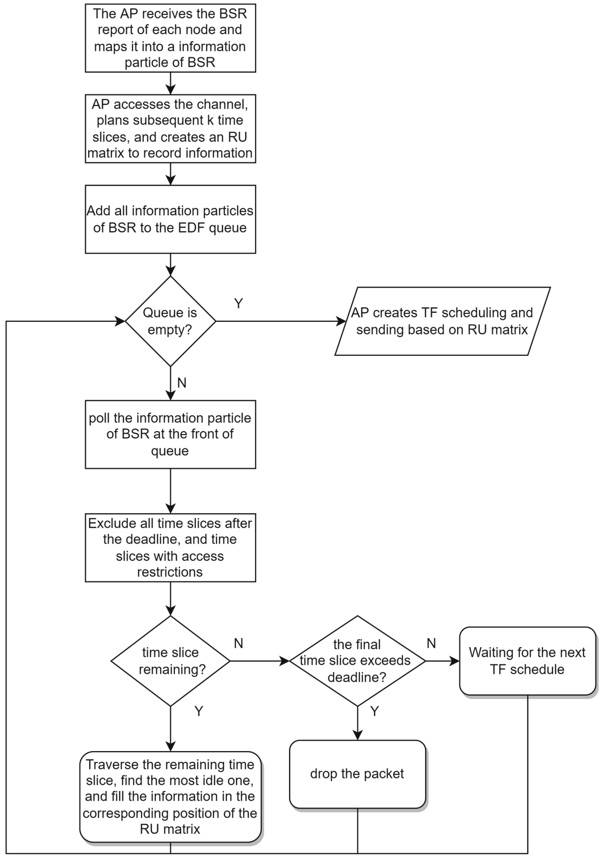


Fig. 2. Flowchart of joint optimization method of scheduling

the information of transmission buffers to the information particles of BSR with the attributes of carrying information and deadline. Finaly, AP adds these information particles of BSR to the EDF queue. At the same time, AP create a empty matrix(number of time slice · number of RU) of RU resource allocation. At this point, the AP perparation stage is over and the scheduling phase begins.

In the scheduling phase, the AP needs to allocate RU to the information particles of BSR in the EDF queue. When the EDF queue is not empty, the AP will get the information particle of BSR from the head of EDF queue. That is, this particle's deadline is the closest among the EDF queue. And then AP will exclude time slices that can not be accessed(including: the time slice is beyond the deadline of the information particle, the RU resources in the time slice are fully occupied, the source STA of this information particle has reached the limit of access ability). If there are still time slice available, then select the time slice, where RU occupies the least, and choose an idle RU to access. That is, fill this information particles of BSR into the matrix of RU resource allocation; If

Algorithm 1 . Joint Optimization Scheduling Algorithm Based on Particle Theory

```
Input: List of BSR information received by AP
Output: Matrix of RU resource allocation
Begin procedure
Map BSR information into BSR information particles (Definition 1)
Put BSR information particles into BSR queue to form Q_BSR, and perform the
  operation Op_inc(Q_BSR)(Definition 3)
AP access the channel and creates an empty matrix of RU resource allocation
while Q_BSR is not empty do
    CurrentPacket ⇐ Q_BSR.poll(), ThisSlice ⇐ The first Time slice
    AssignedTimeSlice ⇐ NULL
    Current minimum Ru usage minRU_num = RU_num
    while ThisSlice is not the last time slice do
        if CurrentPacket.ddl > ThisSlice.endTime then
            if AssignedTimeSlice is NULL then
                CurrentPacket dropped
            end if
            break
        end if
        if CurrentPacket.fromNode reach the max access ability in ThisSlice then
            continue
        end if
        if minRU_num > ThisSlice.usedRU then
            AssignedTimeSlice ⇐ ThisSlice
        end if
    end while
    Fill in the BSR information in the corresponding position in the matrix of RU
      resource allocation
    ThisSlice ⇐ next time slice
end while
End procedure
```

there is no time slice left, it is determined whether the last time slice is within its deadline. If it is, it means it has a chance to wait for the next TF to schedule, else, the information particle must be unable to effectively send, it will be discarded. After completing the traversal of all information particles in the EDF queue, the TF schedules according to the matrix of RU reasource allocation. At this point the AP schedululing phase ends, the specific algorithm is detailed in Algorithm 1, and the random access phase begins.

In random access phase, the packets arrival rule of random users satisfies the Poisson distribution. Random users will select a time slice with idle RU to access when they have packet need to be sent. If an RU is selected by one node, the access is successful; else, it is regared as collision. If the collision happens in more than half of RU after a node access, its backoff window will be doubled. Otherwise, the backoff window will remain the same for rebackoff and access. The detail algorithm can be found in Algorithm 2.

Algorithm 2. Joint optimization random access algorithm

Input: a random user access
Output: RU access
Begin proceduce
1: random user access the channel and create a random backoff value $OBO \in [0, OCW_{min}]$
2: $ThisSlice \Leftarrow$ next time slice recently
3: **if** $OBO \leq ThisSlice.remainRU_{num}$ **then**
4: select $R\_STA.MaxAccessNum$ idle RUs randomly for access
5: **else**
6: $OBO \Leftarrow OBO - ThisSlice.remainRU_{num}$
7: **end if**
8: **if** The number of RUs also selected by other $R\_STAs < R\_STA.MaxAccessNum/2$ **then**
9: this random user access success
10: $R\_STA.collisionNum = 0$
11: goto line 1
12: **else**
13: collision occupies
14: $R\_STA.collisionNum{+}{+}$
15: **if** $R\_STA.collisionNum == MaxCollisionNum$ **then**
16: currentPacket dropped, and goto line 1
17: **else**
18: $OCW \Leftarrow 2OCW$, and recreate a random backoff value $OBO \in [0, OCW]$
19: **end if**
20: **end if**
End proceduce

5 Simulation Verification

This section will introduce the simulation scenarios, related parameters, the simulation group scheme and the comparision group scheme. Finally it give the comparison of performance of following parameters: the average delay of the two groups of schemes in the simulation scenario (the average time taken from the creation of all sending packets to the completion of sending), the throughput (successful transmission per unit time) and the packet loss rate (packet loss: the number of random user collisions reaches the upper limit, and the scheduling user has not been allocated resources until the deadline).

5.1 Introduction to Simulation Platform

This paper uses C++ to build a simulation platform to simulate the uplink scenario. As shown in Fig. 3, in this paper the system is considered as single AP scenario, and there are n STAs associated with AP, among which there are n_s

S-STAs who uses scheduled access with the intensity of its service flow is λ_s, and there are n_r R-STAs who uses random access with the intensity of its service flow is λ_r.

In the IEEE 802.11ax environment, when the AP schedules the uplink service, STAs need to report the information of their transmission buffer through the BSR in advance, and then AP sends a TF to allocate the RU resource to the node. In this paper, the process of BSR is not the focus of consideration, so it is incorporated into the duration of TF.

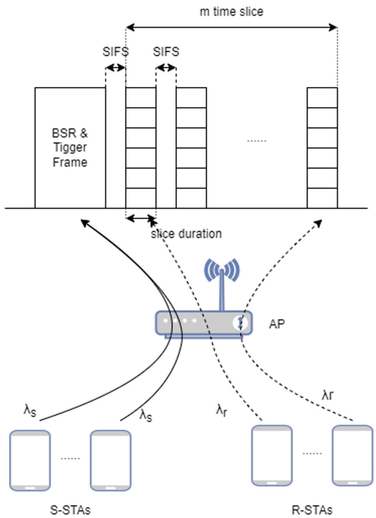


Fig. 3. Schematic diagram of joint access simulation scenario

As shown in Fig. 3, in this paper, the time-frequency resources scheduled by the AP to send TF are divided into m time slices, the length of each time slice (0.8 ms) and the interval between two time slice (16 µs). In addition, this paper limits the maximum RU that a S-STA can access in a single time slice, that is, the node access capacity. The specific simulation platform parameters are shown in Table 1.

Table 1. Table of simulation parameters.

Parameter Name	Value
number of timeslices	50
number of RUs	8
bandwidth of channel(MHz)	20
number of random users	5
number of scheduling users	8
random user traffic vs. scheduled user traffic	1:9
the ability of node access	1
length of a packet(bit)	2000
delay tolerance of packets(ms)	100
OCW_{min}	8
maximum retransmission times of random users	6
simulation duration(ms)	10000

5.2 Introduction to the Simulation Scheme

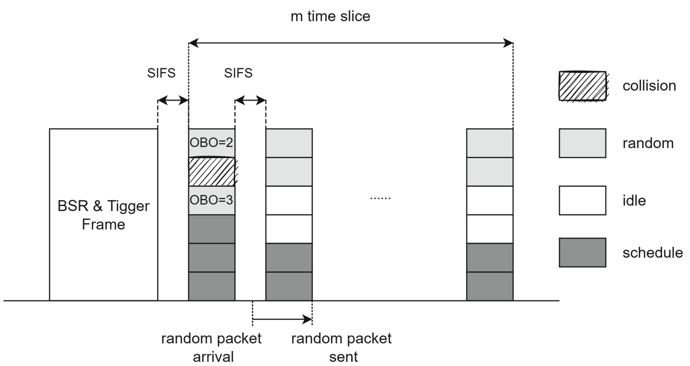


Fig. 4. Flowchart of joint optimization method of scheduling

As shown in Fig. 4, in the simulation scheme of this paper, the AP uses the scheduling access algorithm in the joint optimization method for scheduling and random access to allocate RU resources to the nodes that have reported the BSR. Then the AP sends TF to schedule the corresponding nodes to send in the allocated RU, so that the peak access bandwidth is minimized. In addition, the production packets of random users are completely random in time. Their packets select the nearest idle time slice, and use the UORA method to compete for access to the channel. If a collision occurs with two nodes, their OCWs will be doubled. And these nodes will join the competition of the UORA in the next idle time slice. random access packets will be dropped after their collision times reachs the maximum.

5.3 Introduction to the Comparision Scheme

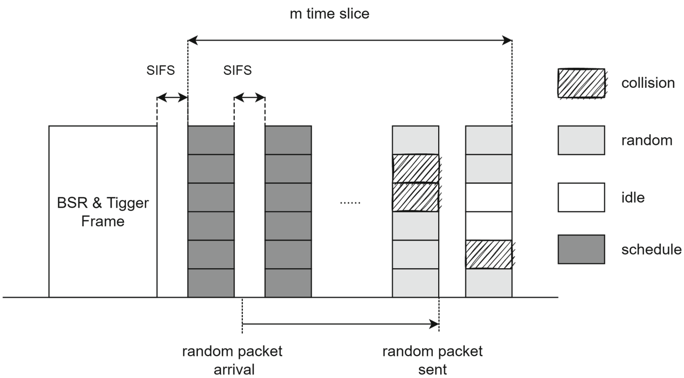
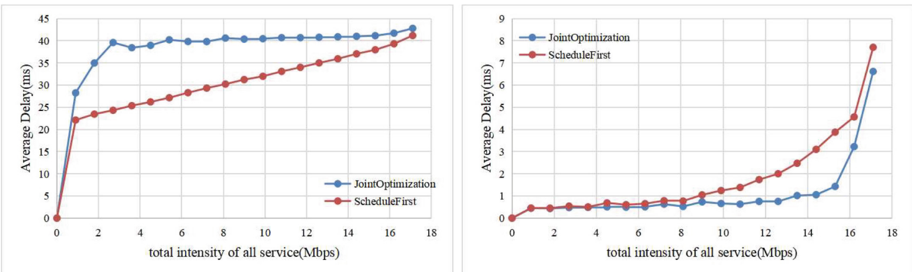


Fig. 5. Flowchart of joint optimization method of scheduling

As shown in Fig. 5, the comparison scheme adopts the currently commonly used scheduling algorithm, and arranges the nodes that have reported BSR in the time slice after TF in turn. The strategy of random users is the same as the simulation scenario.

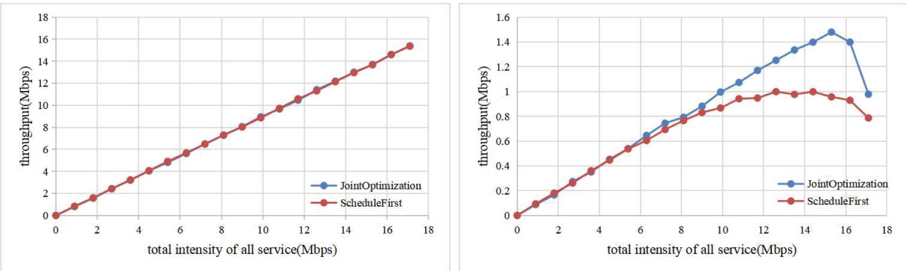
5.4 Analysis of Simulation Results



(a) scheduling access users (b) random access users

Fig. 6. Figure of relationship between average delay and total traffic

As shown in Fig. 6, when the total traffic is small, the delay performance of the two methods is similar. The reason is that when the traffic is low, the random users who need to access in each time slice and the RU occupied by the scheduling users when accessing are less. Therefore, both methods can ensure the delay of random users. However, some scheduling users are allocated to a later time slice due to the minimum access bandwidth requirements of the scheduling algorithm, so the delay of scheduling users is larger. However, with the increase of user traffic, compared with the traditional scheduling first algorithm, random users gradually increase after the total traffic exceeds 8mbps. The joint optimization method can keep the random user delay at a very low level while ensuring the requirement for delay of scheduling users until the total traffic exceeds 14mbps. It can be seen that the joint optimization method can effectively ensure the service delay. As the traffic continues to increase, both scheduling schemes will make all RUs occupied by scheduling users' packets. Therefore, when the traffic is large enough, the performance of the two schemes will be close again.



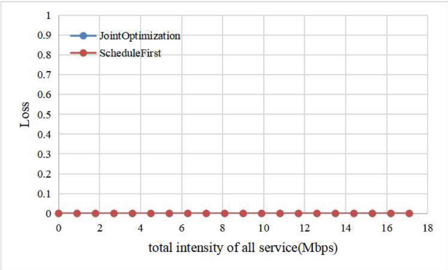
(a) scheduling access users

(b) random access users

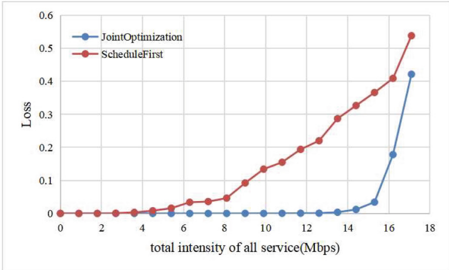
Fig. 7. Figure of relationship between throughput and total traffic

As shown in Fig. 7, the scheduling user throughput performance of the two schemes is completely consistent. As for the random user performance, the throughput performance of the two schemes is similar when the total traffic is small or large. The reason for this phenomenon has been shown in the delay performance analysis. When the total traffic is in the range of 8–17 mbps, the Ru of the comparison scheme is concentrated in the later time slice, and a large number of random users compete in the same time slice. It leads to a high collision probability, which makes the channel utilization low. On the contrary, the experimental scheme makes the Ru distribution as average as possible in time, and it matches the distribution pattern of random users. As a result, the competition is more dispersed in the experimental scheme, which reduces the probability of collision, and thus produces better performance of throughput.

As shown in Fig. 8, the performance analysis of packet loss rate and throughput is similar. Both schemes can fully meet the needs of scheduling users without packet loss. For random users, when the total traffic is large or small, the performance of the two schemes is similar. When the total traffic is in the range



(a) scheduling access users



(b) random access users

Fig. 8. Figure of relationship between throughput and total traffic

of 5–17mbps, referring to the performance analysis of throughput, due to the different distribution of idle Ru in time of the two schemes, the collision probability of the experimental scheme is less than that of the comparative scheme, so the packet loss rate is also better than that of the comparative scheme.

6 Conclusion

This paper proposes a joint optimization method of scheduling and random access based on the idea of particleization. The core idea of this method is to use the theory of particle access to granulate the uplink service flow, and then use an EDF strategy to keep the access bandwidth of the scheduled users always in the minimum access bandwidth, so that the distribution of idle bandwidth is averaged over time, in this way, the probability of collision and waiting time of random user access can be reduced. For random users, the UORA method of IEEE 802.11ax can still be used for random access. The simulation results show that when the traffic flow is suitable, the joint optimization method proposed in this paper can significantly reduce the access delay of random users on the premise of guarantee the requirements for delay of scheduling users. The work in this paper only considers the optimization of uplink hybrid access (scheduling and random access). In the future, we will further study the uplink and downlink access methods based on the idea of particle access to guarantee the requirements for the latency performance of various services.

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