

# Estimating the Number of Nodes in WLANs to Improve Throughput and QoS

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**SUMMARY** WLANs have become increasingly popular and widely deployed. The MAC protocol is one of the important technology of the WLAN and affects communication efficiency directly. In this paper, focusing on MAC protocol, we propose a novel protocol that network nodes dynamically optimize their backoff process to achieve high throughput while supporting satisfied QoS. A distributed MAC protocol has an advantage that no infrastructure such as access point is necessary. On the other hand, total throughput decreases heavily and cannot guarantee QoS under high traffic load, which needs to be improved. Through theoretical analysis, we find that the average idle interval can represent current network traffic load and can be used together with estimated number of nodes for setting optimal CW. Since necessary indexes can be obtained directly through observing channel, our scheme based on those indexes will not increase any added load to networks, which makes our schemes simpler and more effective. Through simulation comparison with conventional method, we show that our scheme can greatly enhance the throughput and the QoS no matter the network is in saturated or non-saturated case, while maintaining good fairness.

**key words:** WLANs, MAC, EDCA backoff, QoS

## 1. Introduction

Wireless local area networks (WLANs) have become increasingly popular and widely deployed. In two channel access methods DCF (Distributed Coordination Function) and an optional centralized PCF (Point Coordination Function), due to inherent simplicity and flexibility, DCF is preferred in the case of no base station. Since all the nodes share a common wireless channel with limited bandwidth in WLANs, it is highly desirable that an efficient and fair medium access control (MAC) scheme is employed. In the case of high traffic, compared to the theoretical upper bound, DCF delivers a much lower throughput [1]. Meanwhile, as demonstrated in [2], the fairness as well as throughput of the DCF could significantly deteriorate when the number of nodes increases.

Although many researches have been conducted to improve throughput and fairness, few of them enhanced both of two performance metrics. In [3]–[5], the works improve throughput and fairness for multirate traffic in saturated case. However, in [3], the MAC frame header contains the additional information, the throughput becomes low in non-saturated case. In [4], [5], these works assume that the system environment is coordinated by an access point

(AP). That is, they do not work without AP. In [6], a method was proposed, which excessively increases CW (Contention Window) to avoid collision that resulting in some wasted time slots under non-saturated case. Moreover, the method adversely affects fairness and so additional fair scheduling mechanism is needed. For mobile networks, estimating the number of nodes is difficult because each node can reach or leave the network freely. Thus, many researches avoid to estimate the number of nodes. In [7], although the number of nodes is estimated, it is complicated and takes time for estimating. The works [8] and [9] observe the average idle interval, adjust the CW in order to obtain higher throughput. These works do not estimate the number of nodes but have an issue that the variation in CW is large, which results in fairness degradation. In [10], based on [8], to improve the problem of fairness which is important for real time communication, authors introduced a method to achieve better fairness but the improvement is not enough. In [11], authors proposed a novel protocol by observing the channel event to estimate the number of nodes and tuning the network to obtain high throughput with good fairness according to the number of nodes. This is proved to be effective.

In the other hand, how to support QoS (Quality of Service) in DCF is another important issue. Though, IEEE 802.11e EDCA (Enhanced Distributed Channel Access) supports QoS for traffics with different priorities. In this paper, we use the method in [11] to tune CW according to each priority to achieve good performance both on throughput and QoS. The related works [12]–[21] proposed several schemes to improve EDCA. In [12], a super slot allocation mechanism is proposed by integrating three time slots into a super slot, each slot in the super slot is allocated to a particular AC (access category) according to its priority to reduce collisions. In [15], each node provides a differentiated control of CW to avoid collision. The way to update CW differs among different priorities of traffic in the case of successful transmission. In [16], when the traffic load is heavy the nodes suspend some transmissions. Although, in [12]–[16], when a collision is occurred, CW is doubled like conventional method, which leads to deteriorate fairness among nodes in the same environment. In [19], considering MAC queue dynamics of each AC and QoS requirements, each node adjusts the delay-based CW. In [21], its proposed method provides real time traffic with the required throughput and delay guarantees. However, the above works do not take fairness into account. In this paper, we aim to enhance throughput, fairness and QoS for EDCA at the same time by

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solving the problems of conventional method and estimating the number of nodes briefly and dynamically. Then, we propose a novel MAC scheme that Optimizing Backoff with better QoS, named as OBQ.

The remainder of this paper is organized as follows. In Sect. 2, we analyze the conventional method and problems. We elaborate on our key idea and the theoretical analysis for improvement in Sect. 3. Then we present our proposed scheme OBQ in detail. Section 4 gives performance evaluation and the discussions on the simulation results. Finally, concluding remarks are given in Sect. 5.

## 2. Conventional Method

### 2.1 Distributed Coordination Function (DCF)

The IEEE 802.11 DCF is based on a mechanism called carrier sense multiple access with collision avoidance (CSMA/CA). In DCF, a node with a packet to transmit initializes a backoff timer with a random value selected uniformly from the range  $[0, CW]$ , where  $CW$  is the contention window in terms of time slots. After a node senses that the channel is idle for an interval called DIFS (DCF interframe space), it begins to decrease the backoff timer by one for each idle time slot. When the channel becomes busy due to other nodes' transmissions, the node freezes its backoff timer until the channel is sensed idle for DIFS. When the backoff timer reaches zero, the node begins to transmit. If the transmission is successful, the receiver sends back an acknowledgment (ACK) after an interval called SIFS (short interframe space). Then, the transmitter resets its  $CW$  to a minimum value  $CW_{min}$ . In the case of collisions, the transmitter fails to receive the ACK from its intended receiver within a specified period, it doubles its  $CW$  until reaching a maximum value  $CW_{max}$  after an interval called EIFS (extended interframe space), chooses a new backoff timer, and start the above process again. When the transmission of a packet fails for a maximum number of times, the packet is dropped.

### 2.2 Enhanced Distributed Channel Access (EDCA)

In IEEE 802.11e, hybrid coordination function (HCF) is defined as the MAC scheme [22], [23]. It includes EDCA and contention-free HCF controlled channel access (HCCA) to support QoS for traffics with different priorities. EDCA is based on CSMA/CA and extends DCF by means of the similar parameters that are used to access the channel. In EDCA, nodes have four ACs, AC[VO] (voice), AC[VI] (video), AC[BE] (best effort) and AC[BK] (background), where AC[VO] is the highest priority while AC[BK] is the lowest priority. Each AC behaves like a virtual station which contends for access to the medium and starts its backoff independently. When a collision occurs among different ACs of the same station, i.e., two backoff counters of ACs reach zero at the same time, the packet of the highest priority AC is transmitted while the lower priority AC performs backoff

again as if a collision occurred. In each AC, there is arbitration interframe space (AIFS) instead of DIFS,  $CW_{min}$ ,  $CW_{max}$  and transmission opportunity (TXOP), respectively. TXOP means that a node transmits multiple packets as long as the duration of the transmissions do not extend beyond TXOP.

### 2.3 Problems

There are several problems in IEEE802.11 DCF. First, the throughput decreases in the case that the number of nodes increases [24]. A collision occurs when two or more nodes start transmitting at the same time. Generally, in WLANs, nodes cannot detect a collision during transmission. The nodes continue transmitting until completing transmission even if a collision occurs. The nodes around transmitter are also affected and waste limited bandwidth. Moreover, when a collision is occurred, the  $CW$  is doubled and a new backoff procedure is started. In theoretical analysis, we can obtain high throughput by using optimal  $CW$  according to the number of nodes. The larger the number of nodes, the larger optimal  $CW$  in order to avoid a collision. In conventional method, since the  $CW$  is reset to  $CW_{min}$  in the case of successful transmission, the number of collisions increases according to the number of nodes and the throughput decreases.

Second, the variation of  $CW$  is large. It means that the variation of the transmission delay is large. Also, the jitter is large and the fairness decreases. To solving these two problems, all nodes always have the  $CW$  around the optimal  $CW$  according to the number of nodes.

Finally, QoS is not guaranteed enough. Since QoS is supported in IEEE 802.11e, the high priority AC transmits with priority and needs to act as the high guarantee of successful transmission. However, since the ranges of the  $CW$ s of the high priority ACs, i.e., AC[VO] and AC[VI], are narrow, QoS becomes low in the case of the number of nodes increasing [22], [23]. Consequently, in this paper, we can solve these problems and enhance both the throughput and the QoS.

## 3. Analysis and the Proposal of Optimizing Backoff by Dynamically Estimating Number of Nodes

Multihop wireless networks are necessary for systems such as vehicle to vehicle communications. The DCF is preferred since it can work without AP. In multihop wireless networks, the throughput becomes low because of hidden terminal problem and multi-channel is an effective method that a group of nodes communicate with a single frequency channel. In this paper, we assume that nodes of network communicate each other using a certain frequency channel in one hop area, while leave the task how to arrange frequency channel to each group as the next work. Here, we try to give an effective protocol with higher throughput and better QoS for one hop area.

As shown in previous research works, the network per-

formance depends principally on  $CW$  and backoff strategy. In this paper, firstly we try to give a more effective method which estimates the number of nodes and calculates the optimal  $CW$  named  $CW_{op}$  for each node to obtain high throughput. Then we can determine  $CW$  for each AC in a node according to its  $CW_{op}$  and QoS requirement.

### 3.1 Optimal Backoff

In the IEEE 802.11 MAC, the  $CW_{op}$  is the key to providing throughput, fairness and QoS. Here, we firstly explain how to obtain the  $CW_{op}$ . In [1], DCF is analyzed based on an assumption that, in each time slot, each node contends for the medium with the same probability  $p$  subject to  $p = 1/(E[B] + 1)$ , where  $E[B]$  is the average backoff timer and equals  $(E[CW] - 1)/2$ . Since our OBQ would enable all the nodes to settle on a quasi-stable  $CW$  shortly after the network is put into operation, for simplicity we assume that all the nodes use the same and fixed  $CW$ . Consequently, we have

$$p = \frac{2}{CW + 1} \quad (1)$$

as all the expectation signs  $E$  can be removed. Channel events can be thought as three types of events, successful transmission, collision, idle. Suppose that every node is an active one, i.e., always has packets to transmit. For every packet transmission, the initial backoff timer is uniformly selected from  $[0, CW]$ . Each virtual backoff time slot is idle, while successful transmission and collision are busy. Accordingly, we denote by  $P_{idl}$ ,  $P_s$ , and  $P_{col}$  the probabilities of the three types of events, respectively. Thus, we can express the above probabilities as

$$\begin{aligned} P_{idl} &= (1 - p)^n \\ P_s &= np(1 - p)^{n-1} \\ P_{col} &= 1 - P_{idl} - P_s \end{aligned} \quad (2)$$

where  $n$  is the number of active nodes. Thus, the throughput is expressed as

$$\rho = \frac{TP_s}{t_{sl}P_{idl} + T_{col}P_{col} + T_{tx}P_s} \quad (3)$$

where  $T$  is the transmission time of packets in one TXOP,  $T_{tx}$  is the successful transmission duration and  $T_{col}$  is the collision duration. For IEEE 802.11e, each node has four ACs, AC[VO], AC[VI], AC[BE] and AC[BK]. Because AC[BK] is close to AC[BE], we take ACs as AC[VO], AC[VI] and AC[BE] in the analysis. In OBQ, we control the transmission opportunity of each AC in a node freely. Thus, the rate of the transmission opportunity of each AC in a node can be expressed by  $\eta_{VO}$ ,  $\eta_{VI}$  and  $\eta_{BE}$ , respectively, which satisfy  $\eta_{VO} + \eta_{VI} + \eta_{BE} = 1$ . Consequently,  $T_{col}$ ,  $T_{tx}$  and  $T$  can be expressed as

$$\begin{aligned} T_{col} &= T_{col\_VO} \cdot \eta_{VO} + T_{col\_VI} \cdot \eta_{VI} \\ &\quad + T_{col\_BE} \cdot \eta_{BE} \end{aligned}$$

$$\begin{aligned} T_{tx} &= T_{tx\_VO} \cdot \eta_{VO} + T_{tx\_VI} \cdot \eta_{VI} \\ &\quad + T_{tx\_BE} \cdot \eta_{BE} \\ T &= T_{VO} \cdot \eta_{VO} + T_{VI} \cdot \eta_{VI} + T_{BE} \cdot \eta_{BE} \end{aligned} \quad (4)$$

where

$$\begin{aligned} T_{col\_VO} &= T_{VO} + EIFS - DIFS \\ &\quad + AIFS[VO] + \tau \\ T_{tx\_VO} &= (T_{VO} + SIFS \cdot 2 + ACK + 2\tau) \\ &\quad \cdot t_{n\_VO} - SIFS + AIFS[VO] \\ T_{VO} &= (T_{data} + T_{head}) \cdot t_{n\_VO} \end{aligned} \quad (5)$$

AC[VI] and AC[BE] are also similar.  $T_{data}$ ,  $T_{head}$  and  $ACK$  represent the transmission time of a MAC frame, header of physical layer and ACK, respectively.  $\tau$  and  $t_{n\_VO}$  are the maximum propagation delay between two nodes and the number of transmissions in one TXOP of AC[VO], respectively. Our aim is to maximize throughput shown in Eq. (3).

In the following, we give the method to estimate the number of nodes on line by three parameters  $P_{idl}$ ,  $P_s$  and  $P_{col}$  which can be obtained directly by listening channel for a certain interval. Then, using obtained  $P_{idl}$ ,  $P_s$  and  $P_{col}$ , we give the method to maximize the throughput dynamically. Calculating number of nodes directly by Eq. (2) is inefficient and unrealistic. Here, we use a simple and effective method which is suitable for real time estimating. From Eq. (2), we have  $P_{idl}/P_s = (1 - p)/(np)$ , then  $p = P_s/(nP_{idl} + P_s)$ . Substitute  $p$  in  $P_{idl} = (1 - p)^n$ , it becomes as

$$P_{idl} = \left(1 - \frac{P_s}{nP_{idl} + P_s}\right)^n \quad (6)$$

Let  $f_{idl}(n) = \left(1 - \frac{P_s}{nP_{idl} + P_s}\right)^n$ , where  $P_{idl}$ ,  $P_s$  and  $P_{col}$  are known parameters and  $n$  is unknown parameter that needs to be estimated. Then when  $f_{idl}(n_0) = P_{idl}$ ,  $n_0$  is the needed value. We find that  $f_{idl}(n)$  is monotone function. We take the derivative of  $f_{idl}$  with respect to  $n$ , and let  $\frac{df}{dn} = \left[\ln\left(1 - \frac{P_s}{nP_{idl} + P_s}\right) + \frac{P_s}{nP_{idl} + P_s}\right] \left(1 - \frac{P_s}{nP_{idl} + P_s}\right)^n$ . It can be found that the second term is always plus. Let  $x = \frac{P_s}{nP_{idl} + P_s}$ , then  $0 \leq x \leq 1$ . Then, the first term of  $\frac{df}{dn}$  becomes  $\ln(1 - x) + x$  which changes from 0 to  $-\infty$  when  $x$  changes from 0 to 1. So, it can be understood that  $\frac{df}{dn}$  is not plus.

With this characteristic, we can estimate the number of nodes by the simple calculation method, without solving a complicated equation. When the number of nodes increases, the monotone function  $f_{idl}(n)$  always decreases. Since  $P_{idl}$  is a known value,  $f_{idl}(n)$  should be adjusted in agreement with  $P_{idl}$ . When  $P_{idl}$  is equal to  $f_{idl}(n)$ ,  $n$  is the real number of nodes in network.

The above character is favorable for estimated number of nodes  $n$  which can be calculated by the following dichotomy. Supposing  $n$  is in a range  $[0, n_{max}]$ , initially let  $n_{try1} = n_{max}/2$  and substitute it into  $f_{idl}(n)$ . Then, compare  $f_{idl}(n_{try1})$  with  $P_{idl}$ . If  $f_{idl}(n_{try1}) > P_{idl}$ , we should set  $n_{try2} = [n_{try1} + n_{max}]/2$ . Otherwise, we should set  $n_{try2} = [n_{try1} + 0]/2$  for the following calculation. Obviously, this method is simple and effective. For example,

when  $n_{max} = 120$ , observing channel events that idle, collision and successful transmission, we just need calculate four times to estimate  $n$  in the worst case with maximum error 3.

In the following, we present the condition of high throughput. The average idle interval is denoted by  $L_{idl}$ , it can be expressed as

$$L_{idl} = \frac{P_{idl}}{1 - P_{idl}}. \quad (7)$$

With Eqs. (1), (2) and (7), this equation can be further written as

$$\begin{aligned} L_{idl} &= \frac{1}{(1 + 2/(CW - 1))^n - 1} \\ &= \frac{1}{n \frac{2}{CW-1} + \cdots + \binom{n}{i} \left(\frac{2}{CW-1}\right)^{n-i} + \cdots + \left(\frac{2}{CW-1}\right)^n}. \end{aligned} \quad (8)$$

We can simplify Eq. (8) as

$$L_{idl} = \frac{CW - 1}{2n}. \quad (9)$$

We can obtain Eq. (9) when  $CW$  is large enough. As a matter of fact, this is the case when the network traffic load is heavy. In this case, to effectively avoid collisions, the optimal  $CW_{op}$  is large enough for the approximation  $L_{idl} = (CW_{op} - 1)/(2n)$  in our OBQ, which is also verified through simulations.

With Eqs. (3) and (9), we can express the throughput as a function of  $L_{idl}$  as shown in Fig. 1. Several important observations are made. First, we find that every curve follows the same pattern; namely, as the average idle interval  $L_{idl}$  increases, the throughput rises quickly at first, and then decreases relatively slowly after reaching its peak. Second, although the optimal value of  $L_{idl}$  that maximizes throughput is different in the case of different frame lengths, it varies in a very small range, which hereafter is called the optimal range of  $L_{idl}$  corresponding to different frame lengths. Finally, this optimal value is almost independent of the number of nodes. Hence, if nodes can estimate the number of nodes correctly, they can set  $CW_{op}$  by  $L_{idl}$  and  $n$  to achieve

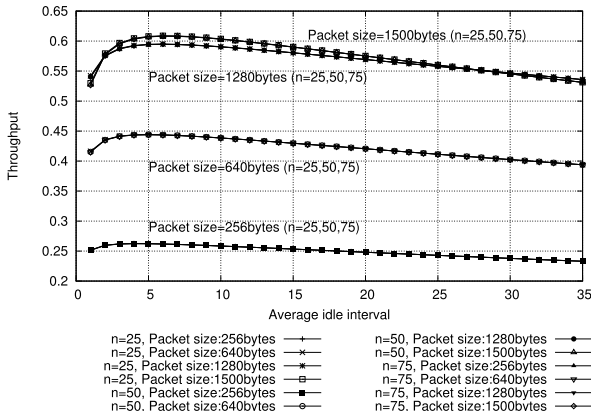


Fig. 1 Throughput vs. average idle interval.

high throughput. Therefore,  $L_{idl}$  is a suitable measure that indicates the network throughput.

In Fig. 1, it can be observed that  $L_{idl}$  is almost a linear function of  $CW$  when  $CW$  is larger than a certain value. Specifically, in the optimal range of  $L_{idl}$ , say  $L_{idl} = [4, 6]$ . From above Eq. (9), according to the number of nodes, each node can set the  $CW_{op}$  that  $CW_{op} = 2nL_{idl} + 1$ . Since we are interested in tuning the network to obtain maximal throughput, given the linear relationship, we can achieve this goal by adjusting the size of  $CW$ . In other words, each node can estimate the number of nodes and adjust its backoff window accordingly such that the total throughput of the network is maximized.

### 3.2 Enhancement of QoS

In above subsection, we introduced a method to maximize total throughput under the condition that all nodes are in the saturation status and the same situation. Here, we use this method to improve EDCA. It is well known that the throughput of each AC in a node is inversely proportional to its  $CWs$  that  $CW[VO]$ ,  $CW[VI]$  and  $CW[BE]$ . Thus, if knowing the  $CW_{op}$  for a node, we can set the optimal  $CW$  of each AC and the total throughput of the node is equal to the total throughput of all ACs.

In this case, there is a difference between IEEE 802.11 and IEEE 802.11e for using OBEN shown in [11]. In EDCA, each node is not always in the same situation that all ACs of each node are saturated. However, this difference does not have serious influence, which can be understood by simulation results given in the following section. For obtaining  $CW$  of each AC, we assume  $\rho_{VO} : \rho_{VI} : \rho_{BE}$  as the transmission opportunity of each AC. The rate of the transmission opportunity of each AC can be expressed as

$$\begin{aligned} \eta_{VO} &= \frac{\rho_{VO}}{\rho_{VO} + \rho_{VI} + \rho_{BE}} \\ \eta_{VI} &= \frac{\rho_{VI}}{\rho_{VO} + \rho_{VI} + \rho_{BE}} \\ \eta_{BE} &= \frac{\rho_{BE}}{\rho_{VO} + \rho_{VI} + \rho_{BE}}. \end{aligned} \quad (10)$$

Also, the attempt probability can be expressed as  $p = 2/(CW_{op} + 1)$  from Eq. (1). Considering from the attempt probability of a node, it becomes  $p = p_{VO} + p_{VI} + p_{BE}$ . From the rate of the transmission opportunity of each AC, the attempt probability of each AC can be expressed as, for example,  $p_{VO} = \eta_{VO} \cdot p = \eta_{VO} \cdot 2/(CW_{op} + 1)$ . Consequently,  $CW$  of each AC can be expressed as

$$\begin{aligned} CW[VO] &= \frac{1}{\eta_{VO}} \cdot (CW_{op} + 1) - 1 \\ CW[VI] &= \frac{1}{\eta_{VI}} \cdot (CW_{op} + 1) - 1 \\ CW[BE] &= \frac{1}{\eta_{BE}} \cdot (CW_{op} + 1) - 1. \end{aligned} \quad (11)$$

Even when nodes are in different state, namely some nodes



have traffic of a part of ACs, this method is effective. In this case, estimated number of nodes differs from a authentic meaning. It becomes as a comprehensive index of network traffic. We prove it by simulation results in Sect. 4. OBQ can offer QoS flexibly by the scheme how to adjust  $CW$  of each AC as shown above. According to the transmission opportunity of each AC, change the delay of each AC but not change the total throughput, OBQ can always maintain the high throughput and provide the satisfied QoS.

### 3.3 OBQ Scheme

With Eq. (6), for estimating the number of nodes, we need to obtain  $P_{idl}$ ,  $P_s$  and  $P_{col}$  by counting the number of idle slots ( $C_{idl}$ ), collisions ( $C_{col}$ ) and successful transmissions ( $C_s$ ) individually. When channel is idle and idle state continues for one slot time, an idle slot is counted and  $C_{idl}$  is increased by one. To avoid occasional cases,  $C_{idl}$ ,  $C_{col}$  and  $C_s$  are expected to be measured in a certain period, for example resetting the counters before a transmission. The  $P_{idl}$ ,  $P_s$  and  $P_{col}$  can be calculated as

$$\begin{aligned} P_{idl} &= \frac{C_{idl}}{C_{idl} + C_s + C_{col}} \\ P_s &= \frac{C_s}{C_{idl} + C_s + C_{col}} \\ P_{col} &= \frac{C_{col}}{C_{idl} + C_s + C_{col}}. \end{aligned} \quad (12)$$

We can obtain the  $CW_{op}$  by Eq. (9) with estimated number of nodes. Then, each node can adjust its  $CW_{op}$  dynamically and tune the network to achieve high throughput. With obtained  $CW_{op}$  and the transmission opportunity of each AC,  $CW$  is set to each AC. According to the QoS requirement,  $CW$  ratio in Eq. (11) can be set freely. In following, we give the tuning algorithm.

1. A node, say Node A, begins listening channel and counts events of idle slot, successful transmission and collision individually.
2. When Node A needs backoff and the number of packet transmissions reaches a certain number, calculates the  $CW_{op}$  as new  $CW$ .
3. With the new  $CW$  and the trasmission opportunity of each AC,  $CW$  is set to each AC, and then it returns to 1).

Ideally, each node should have the same  $CW$  when the network enters into steady state in saturated case; in reality, each node set its  $CW$  around the  $CW_{op}$ . Using this scheme, high throughput, good fairness and satisfied QoS are achieved, which can be found in the following simulations.

## 4. Performance Evaluation

In this section, we evaluate the performance of our OBQ through simulations, which are carried out on OPNET Mod-

**Table 1** Network configuration.

Parameter	Value
SIFS	10μsecs
Slot time	20μsecs
EIFS	364μsecs
AIFS[VO]	50μsecs
AIFS[VI]	50μsecs
AIFS[BE]	70μsecs
TXOP[VO]	3264μsecs
TXOP[VI]	6016μsecs
TXOP[BE]	0
$CW_{min}[VO] \sim CW_{max}[VO]$	7 ~ 15
$CW_{min}[VI] \sim CW_{max}[VI]$	15 ~ 31
$CW_{min}[BE] \sim CW_{max}[BE]$	31 ~ 1023
Max retry threshold	7
Buffer size	256000 bits
Background noise	-101dBm
Data rate	11Mbps

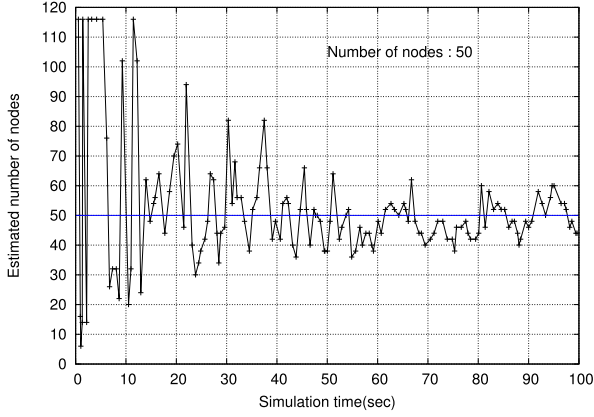
**Table 2** Backoff parameters.

Parameter	Value
Maximum number of nodes	120
$L_{idl}$	5

eler [25]. For comparison purpose, we also present the simulation results for the IEEE 802.11e EDCA. IEEE 802.11b is adopted as the wireless medium. The simulation parameters of IEEE802.11e are shown in Table 1 and the OBQ-specific parameters in Table 2. In IEEE 802.11e, sets the minimum or maximum  $CW$  of each AC, but in OBQ, there is no lower or upper bound of  $CW$  of each AC. Not thinking a specific application, we assume network nodes are distributed at random in a round area with diameter of 200 meters and each node generates traffic according to a Poisson process with the same arrival rate. Each node selects a node in the center of a round area as a receiver. The arrival rate is kept increasing until the network is saturated. The transmission opportunity of each AC should be set according to the QoS requirement. However, since the QoS requirement is not assumed in particular, all nodes have three ACs. The transmission opportunity of each AC is set to  $\rho_{VO} : \rho_{VI} : \rho_{BE} = 15 : 10 : 1, 60 : 20 : 1$ , simulations are carried out in two patterns. For the approximation  $\frac{1}{\rho_{VO}} : \frac{1}{\rho_{VI}} : \frac{1}{\rho_{BE}} = CW[VO] : CW[VI] : CW[BE]$ ,  $CW$  is set to each AC. As shown below, OBQ exhibits a better performance.

### 4.1 Estimating Number of Nodes

OBQ can estimate the number of nodes dynamically in saturated case. Figure 2 shows the estimated number of nodes of a node with condition of 50 nodes in offered load 1. From Fig. 2, we find that estimated number of nodes changes to big value close to 120 because all nodes begin to transmit at same time from the beginning of simulation and then converges to a comparatively stable value around 50 after a short time about 13s which is related to algorithm of backoff parameters shown in Table 2.

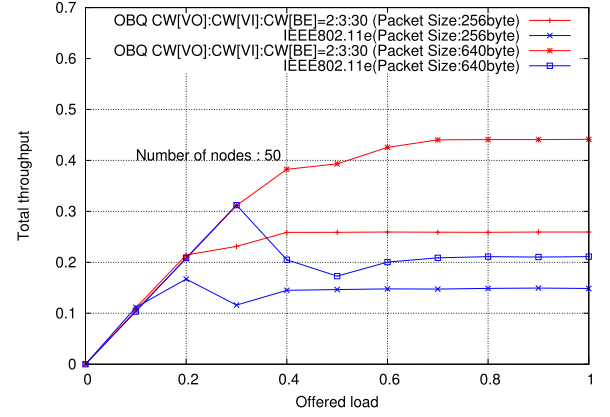


**Fig. 2** Estimated number of nodes vs. simulation time.

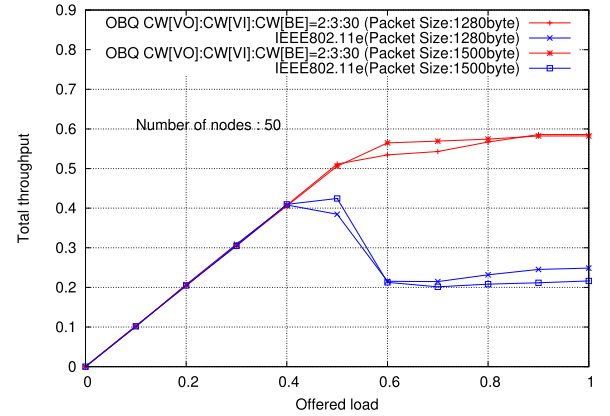
## 4.2 Throughput

First, since all nodes can obtain the almost same total throughput, we present the total throughput of AC[VO], AC[VI] and AC[BE] for the two schemes, i.e., OBQ and the IEEE 802.11e, under different offered load and packet sizes. Unless otherwise noted, OBQ sets  $CW$  ratio,  $CW[VO] : CW[VI] : CW[BE] = 2 : 3 : 30$ , as one example. Figures 3, 4 show the total throughput results when the number of nodes is 50 and the packet sizes are 256, 640, 1280 and 1500 bytes, respectively. In figures, vertical axis expresses normalized total throughput which is the ratio of actual total throughput to network data rate (11Mbps) and horizontal axis expresses normalized offered total traffic. Note that the packet size is the size of payload data and does not include MAC overhead, which is one reason that the simulation results are lower than the theoretical value. In Fig. 3, we can find that when the traffic load is low, say lower than 0.2, the total throughput of OBQ with short packet size 256 bytes is similar to the IEEE 802.11e but a little difference. The total throughput is tiny more than offered load because of Poisson arrival used for packet generation. In offered load 0.2, the total throughput of IEEE 802.11e is lower than offered load, which mean packet loss. In contrast, the total throughput of OBQ is almost equal to offered load. When the offered load is larger than 0.3, the total throughputs of OBQ and IEEE 802.11e are lower than offered load and reach saturation. The maximum total throughput of OBQ is 0.26 which is higher than 0.17 of the IEEE 802.11e in the case of 256 bytes. Improvement reaches to 53%. In the case of packet size 640 bytes, the maximum total throughputs of OBQ and IEEE 802.11e increase. In Fig. 4, the packet sizes are set as 1280 and 1500 bytes longer than above case. The same change tendency can be found like Fig. 3. The improvement of total throughput in the saturation case becomes higher in the case of longer packet size, which reaches about 2.7 times in the case of 1500 bytes packet. Figure 5 shows the total throughputs when the  $CW$  ratio is changed. The  $CW$  ratio has a little effect on the total throughput performance.

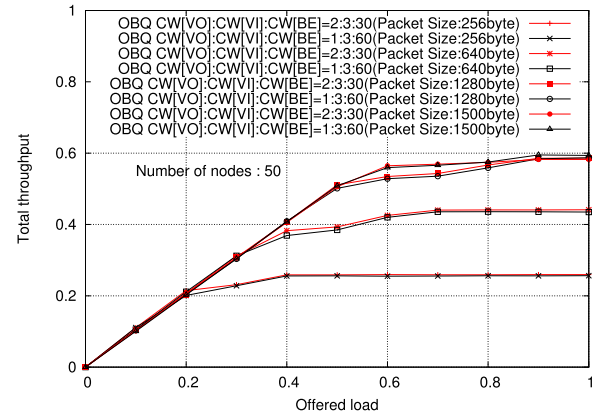
Figure 6 shows the maximum total throughputs with



**Fig. 3** Total throughput of OBQ and IEEE 802.11e with different packet size.



**Fig. 4** Total throughput of OBQ and IEEE 802.11e with different packet size.



**Fig. 5** Total throughput vs. offered load when the  $CW$  ratio is changed.

different packet sizes. Because the  $CW$  ratio has a little effect on the total throughput performance, Fig. 6 shows only the result of the  $CW$  ratio,  $CW[VO] : CW[VI] : CW[BE] = 2 : 3 : 30$ , as one example. As shown in the figure, when packet size increases, the total throughput of OBQ rises and OBQ is not so sensitive to changes in the number of nodes because of optimized  $CW$ . In contrast, IEEE 802.11e is

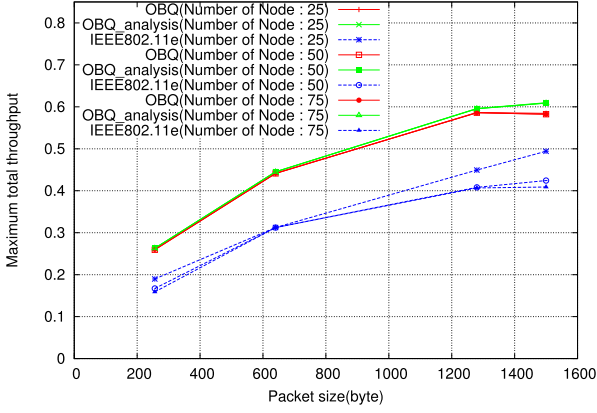


Fig. 6 Maximum total throughput with different frame lengths.

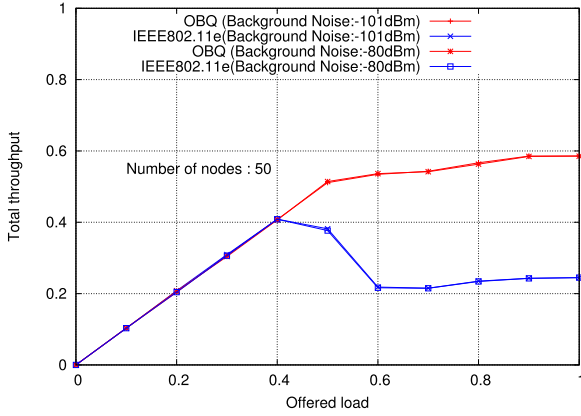


Fig. 7 Total throughput vs. offered load when the background noise varies.

sensitive to changes in the number of nodes and the total throughputs of IEEE 802.11e become low as the number of nodes increases. Moreover, OBQ remains very close to the analysis of OBQ in Eq. (3), maximum error about 4%.

We evaluate the performance of our OBQ in an environment close to the real world. Figure 7 shows the total throughput when the background noise varies. The accuracy of the channel listening is degraded when background noise increases. However, OBQ has little effect on the total throughput in background noise  $-80$  dBm, which is shown as in the figure that two lines with different background noise are almost same. To clarify the effects of traffic patterns, Fig. 8 shows the total throughput when the traffics vary. In Fig. 8, 25 nodes generate traffics according to a Poisson process and 25 nodes generate traffics according to a constant rate. The total throughputs are almost similar in fully non-saturated case and saturated case. The total throughputs are slightly different in the border around non-saturated case and saturated case but the effects of an arrival distribution are practically negligible.

#### 4.3 Delay

Figures 9, 10 show the delay and the throughput results of

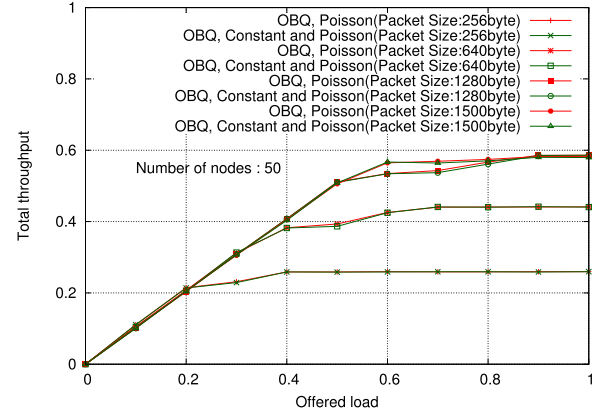


Fig. 8 Total throughput vs. offered load when the traffics vary.

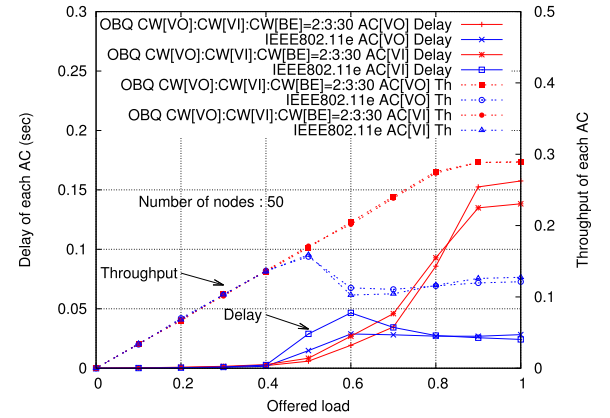


Fig. 9 Delay and throughput of AC[VO] and AC[VI] vs. offered load.

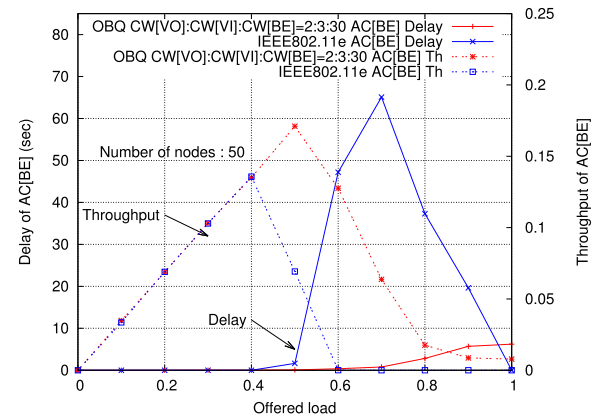
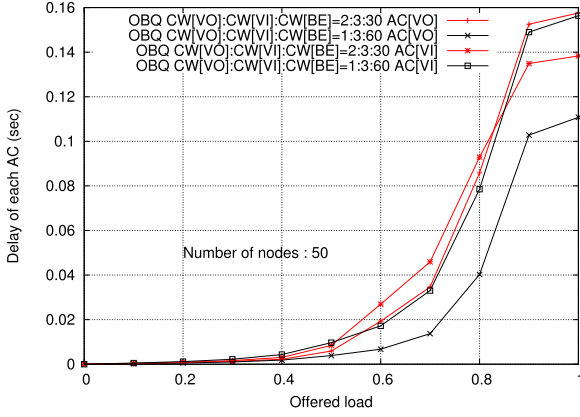
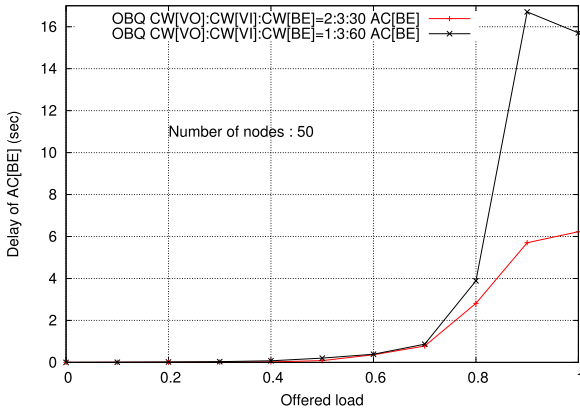


Fig. 10 Delay and throughput of AC[BE] vs. offered load.

each AC when the number of nodes is 50 and the packet size is 1280 bytes since it is the same tendency even if packet size is changed. The delay is the time from head of the transmission queue to receiving ACK, does not include the time of queuing. Figure 9 shows the delay and the throughput results of AC[VO] and AC[VI]. When the offered load is less than 0.7, i.e. non-saturated case, the delay of OBQ is lower than that of the IEEE 802.11e. However, from offered load



**Fig. 11** Delay of AC[VO] and AC[VI] vs. offered load when the CW ratio is changed.



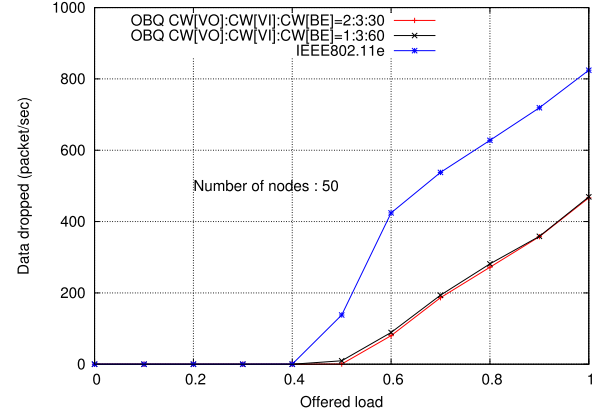
**Fig. 12** Delay of AC[BE] vs. offered traffic when the CW ratio is changed.

is 0.7, i.e. saturated case, the delay of OBQ is higher than that of the IEEE 802.11e. It is because that part of delay of IEEE 802.11e of dropped packets is ignored, which does not mean the delay characteristics is good. We describe in detail in the next section of data dropped. Figure 10 shows the delay and the throughput results of AC[BE]. The delay of OBQ is always lower than that of the IEEE 802.11e, except offered load 1 since throughput of AC[BE] of IEEE 802.11e is 0 then. The throughput of each AC of OBQ is always higher than that of IEEE 802.11e.

Figures 11, 12 show the delay results of each AC when CW ratio is changed. Figure 11 shows the delay results of AC[VO] and AC[VI]. The delay is changed according to CW ratio. Figure 12 shows the delay result of AC[BE]. The same change tendency can be found like Fig. 11. Thus, the delay of each AC of OBQ changes but the changes of total throughput are not clearly when CW ratio is changed.

#### 4.4 Data Dropped

Figure 13 shows the data dropped results with 50 nodes and the packet size 1280 bytes. Packets are dropped due to buffer overflow and retry threshold exceeding. In figure, vertical



**Fig. 13** Data dropped vs. offered traffic when the CW ratio is changed.

axis expresses the sum of buffer overflow and retry threshold exceeded and horizontal axis expresses normalized offered total traffic. As shown in Figs. 3, 4, 5, OBQ maintains high throughput even if CW ratio is changed. Therefore, the data dropped is minimized even if CW ratio is changed. For IEEE 802.11e, the number of dropped packets increases fast from offered load 0.5 which the network becomes saturated as shown in Fig. 4. In contrast, OBQ becomes saturated from offered traffic 0.6.

It is found that the delay of the IEEE 802.11e is lower than that of OBQ in saturated case. The reason is that the IEEE 802.11e has the CW much lower than the  $CW_{op}$ , and the throughput decreases though the delay is lower than that of OBQ. IEEE 802.11e has much data dropped by retry threshold exceeding but OBQ hardly has that. Also, OBQ can achieve better throughput and delay performance than IEEE 802.11e by restricting delay of each AC. Thus, IEEE 802.11e has extremely low guarantee for successful transmission. In contrast, OBQ minimizes the data dropped and obtains high throughput.

#### 4.5 Fairness

To evaluate the fairness of OBQ, we adopt the following Fairness Index (FI) [26] that is commonly accepted:

$$FI = \frac{(\sum_{i=1} T_i / \phi_i)^2}{n \sum_{i=1} (T_i / \phi_i)^2} \quad (13)$$

where  $T_i$  is total throughput of flow  $i$ ,  $\phi_i$  is the weight of flow  $i$  (normalized total throughput requested by each node). Here, we assume all nodes have the same weight in simulation. According to Eq. (13),  $FI \leq 1$ , where the equation holds only when all  $T_i / \phi_i$  are equal. Normally, a higher FI means a better fairness.

Figure 14 shows the fairness index of OBQ and the IEEE 802.11e when packet size is 1280 bytes. It can be found that the fairness of OBQ within 8s periods is significantly improved over that of the IEEE 802.11e. It can also be seen that as the number of nodes rises, the fairness drops quickly for the IEEE 802.11e, whereas for OBQ, the fairness only slightly decreases. OBQ can obtain better fairness



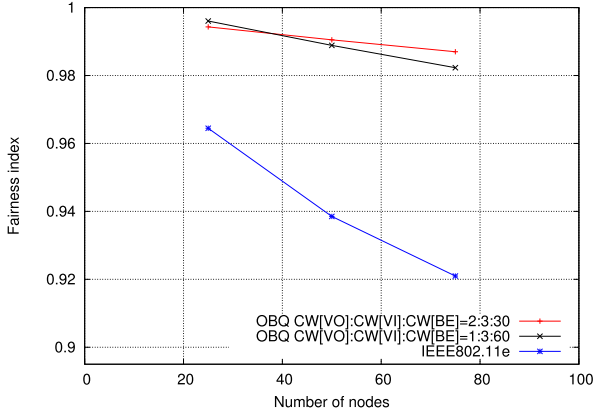


Fig. 14 Fairness index when the CW ratio is changed.

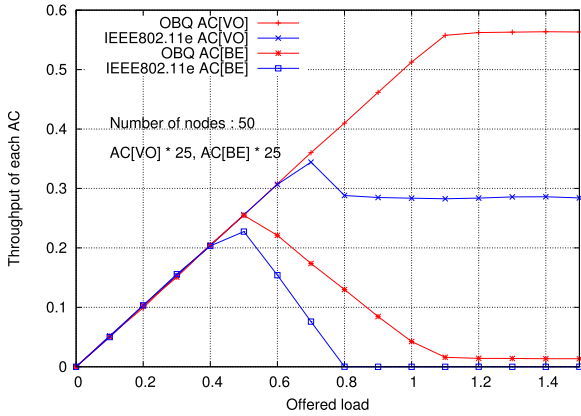


Fig. 15 Throughput of each AC vs. offered load when the traffic configuration is changed.

than IEEE 802.11e even if CW ratio is changed. This is because OBQ ensures that all the nodes use about the same CW that is around the optimal value.

#### 4.6 Effect of Traffic Configuration

Until now, the simulation parameter is that all nodes have three ACs, thus AC[VO], AC[VI] and AC[BE]. In this section, we set nodes with different ACs that 25 active nodes with only AC[VO] and 25 active nodes with only AC[BE]. Other simulation parameters are the same in the above section. Packet size is 1280 bytes and CW ratio  $CW[VO] : CW[VI] : CW[BE] = 2 : 3 : 30$ . Figure 15 shows the throughput results of each AC. In figure, vertical axis expresses normalized throughput of each AC and horizontal axis expresses normalized offered total traffic. In the case of IEEE 802.11e, the throughput of higher priority AC[VO] is saturated from offered load 0.6 and decreases. Whereas for OBQ, the throughput of that increases until offered load 1.1 and reach saturation. Improvement reaches to about 2 times in offered load 1.5. The throughputs of lower priority AC[BE], both IEEE 802.11e and OBQ, decrease from a certain offered load. In the case of IEEE 802.11e, throughput decrease sharply from offered load 0.5. This is due to the

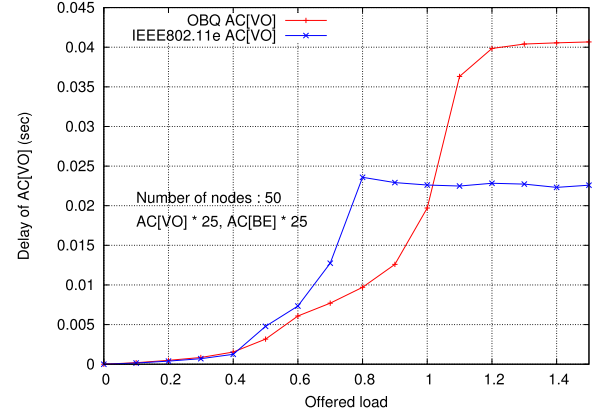


Fig. 16 Delay of AC[VO] vs. offered load when the traffic configuration is changed.

reason that the variation of CW in IEEE 802.11e cannot be adjusted to optimal value for the increased traffic of higher priority. Not like IEEE 802.11e, OBQ always obtains high throughput of AC[BE] and has less interference from the increased traffic.

Figure 16 shows the delay results of AC[VO]. In Fig. 16, the delay of OBQ is lower than that of the IEEE 802.11e in non-saturated case but not in saturated case like Fig. 9. In the case of IEEE 802.11e, delay is low in saturated case, however, throughput is low and much data dropped are caused by retry threshold exceeding because IEEE 802.11e has the CW much lower than the  $CW_{op}$  and the range between  $CW_{min}[VO]$  and  $CW_{max}[VO]$  is narrow. In contrast, OBQ has around the  $CW_{op}$  due to obtain high throughput and provide the satisfied QoS even if traffic configuration is changed, that is, all nodes do not have three ACs.

## 5. Conclusion

In this paper, we proposed a novel MAC protocol OBQ that enhances EDCA. In OBQ, each node observes three types of channel events, idle, successful transmission and collision to estimate the number of nodes and then sets optimal CW dynamically according to the number of nodes. Thus, OBQ can obtain high throughput. With optimal CW and CW ratio according to the QoS requirement, each node sets CW for each AC separately, which leads to better QoS. Even if the traffic situation of each node changes, total throughput always maintains high throughput.

From analysis and simulation results, this scheme is effective and can adjust the network change promptly. Moreover, OBQ solves the problems of conventional method and can achieve higher throughput and better QoS than IEEE 802.11e. All nodes with same traffic can have the almost same CW around the optimal value, which means a high fairness. As a future work, we need verify by actual environment and evaluate the validity of OBQ and extend OBQ to multihop wireless networks by multiple frequency channels.

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