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Performance Improvements of Multi-hop Ad Hoc Wireless Networks in Distributed Cooperative systems

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Chapter 1

Introduction

1.1 Abstract

Wireless local area networks(WLANs) have become increasingly popular and widely deployed. 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) protocol is employed. The fundamental access method of the IEEE802.11 (The Institute of Electrical and Electronics Engineers) MAC is a DCF (Distributed Coordination Function) and an optional centralized one called Point Coordination Function(PCF). Due to its inherent simplicity and flexibility, the DCF is preferred in the case of no base station such as vehicle to vehicle communications. In DCF, there are three problems as follows. First, the throughput decreases when the number of nodes increases. Second, The variation of the Contention Window(CW) is large, which means that the fairness decreases. Finally, QoS is not guaranteed enough. To improve QoS(Quality of service) in DCF, the IEEE 802.11e has defined EDCA(Enhanced Distributed Channel Access). Specifically, the throughput and the fairness decrease sharply as the number of nodes increase in EDCA or multi-hop network.

The focus of this thesis is on DCF and EDCA assuming the vehicle to vehicle communications. In vehicle to vehicle communications, each node can reach or leave the network freely. When much nodes enter network, the throughput and fairness decreases sharply. To deploy a flexible and efficient network, the above problems need to be resolved. Thus, this thesis presents the MAC protocols to resolve the above problems through 3 steps. First, I propose a new novel MAC protocol OBEN (Optimizing Backoff by dynamically Estimating Number of Nodes). OBEN assumes the single-hop network with DCF. In OBEN, each node can estimate the number of nodes, obtain the optimal CW and achieve the high throughput and good fairness. Second, I propose OBQ (Optimizing Backoff with better QoS). OBQ is based on OBEN and takes QoS into account. OBQ also can achieve

the high throughput and good fairness. Additionally, according to the QoS requirement, each node sets CW for each AC separately, which leads to better QoS. Finally, I propose OBEM(Optimizing Backoff by dynamically Estimating the number of nodes in Multi-hop networks). OBEM expands OBEN in multi-hop wireless networks. In multi-hop wireless networks, the throughput decreases heavily under a high traffic load due to the hidden node problem. OBEM can alleviate the hidden node problem and enhance the throughput and the fairness. Through simulations comparison with the conventional method, this thesis shows that OBEN, OBQ and OBEM can greatly enhance the throughput.

1.2 Construction of the thesis

The remainder of this thesis is organized as follows. The Chapter 2 explains the conventional method, DCF and EDCA. The IEEE 802.11 DCF and EDCA are based on a mechanism called carrier sense multiple access with collision avoidance(CSMA/CA). 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, it begins to decrease the backoff timer by one for each idle time slot. When the channel becomes busy due to other node's transmissions, the node freezes its backoff timer. When the backoff timer reaches zero, the node begins to transmit. If the transmission is successful, the transmitter resets its CW to CW_{min}. In the case of collision, it doubles its CW until reaching a maximum value CW_{max}. The transmitter chooses a new backoff timer and starts the above process again. Also, this chapter introduces the problems characteristic of multi-hop wireless network. Specifically, those problems are the hidden node problem, exposed node problem and receiver blocking problem. For the throughput analysis in multi-hop wireless network, those problems are important factors.

In Chapter 3, I propose a MAC protocol OBEN, which can improve the throughput and the fairness in single-hop wireless network. In DCF, each node performs the carrier sense and transmits a packet after random wait time. For this random wait time, when the number of nodes increases, the collision is occurred and the throughput decreases. Also, CW is the value related to the node's packet transmission probability, a small CW results in a high collision probability, whereas a large CW results in wasted idle time slots and throughput decreases. Because the variation of CW is large in the conventional method DCF, there are problems that the throughput and the fairness are low. To resolve the above problems, I propose a new MAC protocol OBEN. In OBEN, firstly, each node listens to the wireless channel. The wireless channel events can be thought of as three types of events, successful transmission, collision and idle. Each node observes the three channel events, computes the probabilities of each channel events and estimates the number of nodes. Second, based on the number of estimated nodes, each node obtains the optimal CW to achieve high throughput. Therefore, each node dynamically estimates the number of nodes, obtains the optimal CW according to the number of estimated nodes, OBEN achieve the high throughput and the good fairness. Through simulation comparison with the conventional method DCF and the recently proposed methods, this chapter shows that our scheme can greatly enhance the throughput with good fairness.

In Chapter 4, I propose a MAC protocol OBQ, which can be improve the throughput and the fairness in single-hop wireless network with QoS. IEEE 802.11e has defined the access method EDCA which expands DCF and supports QoS for traffics with different priorities. In EDCA, in addition to the problems of the conventional method DCF, there is a problem that QoS is not guaranteed enough. The node has four AC(Access Category) with different priorities. 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 of the high priority AC is narrow, QoS becomes low in the case of the number of nodes increasing. The proposal method OBQ is a new MAC protocol that is based on OBEN and resolves the above problems. In OBQ, based on OBEN, each node estimates the number of nodes through observing the wireless channel. Based on the number of estimated nodes, each node obtains the optimal CW. With the optimal CW and the transmission opportunity of each AC, CW is set to each AC. OBQ controls the transmission opportunity of each AC in a node freely according to QoS requirement. The delay of each AC is changed depending on the transmission opportunity of each AC but the total throughput of ACs is not changed. Through simulation comparison with the conventional method DCF, OBQ always maintain the high throughput and provide the satisfied QoS.

In Chapter 5, I propose a MAC protocol OBEM, which can be improve the throughput and the fairness in multi-hop wireless network. OBEN and OBQ assume that the network is in single-hop wireless network, which all nodes are in the communication range. In multi-hop wireless network, the throughput sharply decreases as compared to single-hop when the number of nodes increases. One of the factors is the hidden node problem. RTS/CTS mechanism, which is defined in IEEE 802.11, is used to alleviate the hidden node problem but not enough. Also, because the analysis in multi-hop wireless network becomes complicated by the hidden node problem, the optimal CW according to the number of nodes was not sufficiently studied. Due to this, this chapter proposes a new MAC protocol OBEM. OBEM is based on OBEN and applied in multi-hop wireless network. In OBEM, each node observes the wireless channel and computes the probabilities of each wireless channel. Each node estimates the number of neighbor nodes and the hidden nodes by using the probabilities of each wireless channel and then obtains the optimal CW. Through simulation comparison with the conventional method DCF, this chapter shows that OBEM achieves the high throughput and good fairness.

Finally, the Chapter 6 comprehensively summarizes the results of the research and arrange for future tasks. First, I propose a distributed MAC protocol OBEN. OBEN can estimate the number of nodes dynamically, obtain the optimal CW and then achieve the high throughput and good fairness. Even if the number of nodes is changed, OBEN can adjust the optimal CW dynamically and obtain better performance than the conventional method DCF and the recently proposed methods. Second, based on OBEN, I propose a distributed MAC protocol OBQ. Using the number of estimated nodes, each node obtains the optimal CW. With the optimal CW and the transmission opportunity of each AC, the CW of each AC is set. OBQ control the transmission opportunity of each AC in a node freely according to QoS requirement. The delay of each AC is changed depending on the transmission opportunity of each AC but the total throughput of ACs is not changed. Finally, for the method that adapts to a wider wireless network, I propose a distributed MAC protocol OBEM. Each node dynamically estimates the number of neighbor nodes and hidden nodes, adjust the optimal CW and then alleviate the hidden node problem. Based on detail analysis and simulation results, the proposal MAC protocol achieves high throughput, good fairness, satisfied QoS and adapting to multi-hop wireless network. Thus, it can be established as a communication technology adapted to distributed wireless networks such as vehicle to vehicle communications.

Chapter 2

Conventional wireless communication systems

2.1 IEEE 802.11 standards

IEEE 802.11 standards defined the specific rules for WLANs communication in 1997 [1]. In first generation technology, the maximum throughput of IEEE 802.11 was 2Mbps. IEEE 802.11 was quickly improved and made by IEEE 802.11a and IEEE 802.11b in 1999. IEEE 802.11a operated in 5GHz bands and maximum throughput is 54Mbps. IEEE 802.11b operated in 2.4GHz bands and maximum throughput is 11Mbps. After IEEE 802.11a and IEEE 802.11b, WLANs technologies have improve every year and new standards have been defined as shown in Table 5.1. IEEE 802.11g was defined in 2003 and replaced the older IEEE 802.11b. Subsequently, IEEE 802.11g was replaced by IEEE 802.11n and newer standard. IEEE 802.11n supports four spatial streams 4×4 MIMO (Multiple Input Multiple Output) and a band width of 40MHz. On the other hand, the newer IEEE 802.11ac supports eight spatial streams 8×8 MIMO and a band width of 80MHz, which can be combined to make 160MHz. Moreover, IEEE 802.11ac supports 256-QAM modulation, while IEEE 802.11n supports up from 64-QAM. With such a huge difference, maximum throughput of IEEE 802.11ac is 7Gbps. In this way, the WLANs technologies have improved and the maximum throughput have increased.

2.2 IEEE 802.11 architecture

The IEEE 802.11 architecture contains several service set: the basic service set (BSS) and the independent BSS (IBSS). The BSS is a wireless network which consists of a single wireless access point (AP) supporting one or multiple wireless stations (STAs), as shown in Fig 2.1. The IBSS is a wilreless network which consists of multiple STAs, as shown in Fig 2.2. BSS is lower

Table 2.1: List of IEEE 802.11 standards

IEEE 802.11 standard	Establishment year	band	maximum throughput
IEEE 802.11	1997	2.4GHz	2Mbps
IEEE 802.11a	1999	5GHz	54Mbps
IEEE 802.11b	1999	2.4GHz	11Mbps
IEEE 802.11g	2003	2.4GHz	54Mbps
IEEE 802.11n	2009	2.4/5GHz	600Mbps
IEEE 802.11ac	2013	5GHz	7Gbps

collisions than IBSS due to the STAs are controlled by a AP in BSS. Hence, the throughput of BSS is higher than that of IBSS in saturated network. On the other hand, IBSS can communicate each other without AP, which means that a wireless network can be constructed at low cost. This thesis focuses on IBSS.

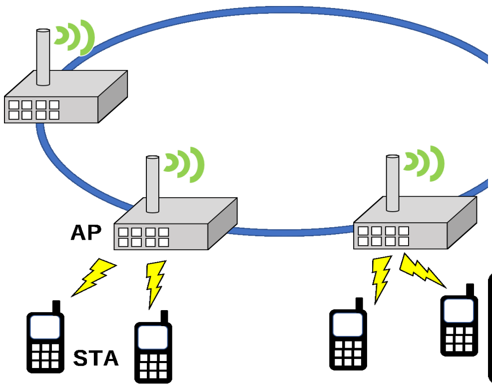


Figure 2.1: BSS

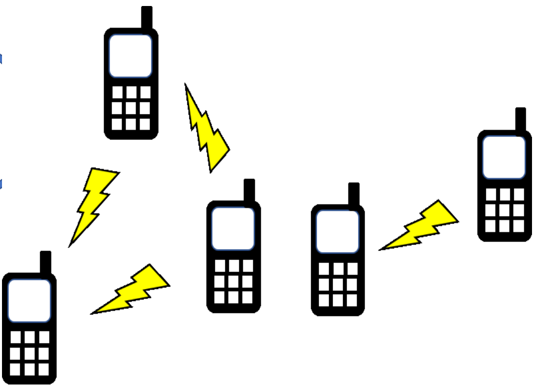


Figure 2.2: IBSS

2.3 DCF

In IEEE 802.11, the Distributed Coordination Function (DCF) and the Point Coordination Function (PCF) is defined. DCF is the fundamental access method and used in BSS and IBSS. DCF is a random access scheme, which is based on the carrier sense multiple access with collision avoidance (CSMA/CA). The waiting duration for packet transmission is calculated with the binary exponential backoff algorithm. On the other hand, PCF is an optional centralized scheme which is only used in BSS. In PCF, the AP operate the STAs and entitle the STA to transmit packets. Due to this, the collision is not occurred in PCF. However, in DCF, there is not a operator for packet transmission, which is occurred many collisions. This thesis focuses on DCF and explain in detail about DCF as the following.

The 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 inter-frame space), it begins to decrease the backoff timer by one for each idle time slot. When the channel becomes busy due to other node's 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 inter-frame space). Then, the transmitter resets its CW to CW_{min}. In the case of collision, the transmitter fails to receive the ACK from its intended receiver within a specified period, with the result that it doubles its CW until reaching a maximum value CW_{max} after an interval called EIFS (extended inter-frame space). The transmitter chooses a new backoff timer and starts the above process again. When the transmission of a packet fails for a maximum number of times, the packet is dropped.

For decreasing the collision and alleviating the hidden node problem (explains in Section 2.5.2), RTS/CTS (Request To Send/Clear To Send) mechanism is used [2]. The Fig. 2.3 shows the RTS/CTS/DATA/ACK mechanism. The source transmits the RTS packet before data transmission. The destination sends back the CTS packet after receiving the RTS packet and waiting for the SIFS. The others which received the RTS packet or the CTS packet wait for the NAV (Network Allocation Vector) duration. The NAV duration is calculated as

$$\begin{aligned} NAV_{RTS} &= T_{CTS} + T_{DATA} + T_{ACK} + 3 * SIFS \\ NAV_{CTS} &= T_{DATA} + T_{ACK} + 2 * SIFS \end{aligned} \tag{2.1}$$

where NAV_{RTS} and NAV_{CTS} are the NAV duration which is distributed via RTS packet and CTS packet, respectively. T_{CTS}, T_{DATA} and T_{ACK} are the transmission duration for a CTS packet, a DATA packet and a ACK packet, respectively. Using RTS/CTS mechanism, the source can reserve the medium for the NAV duration, which result that nodes avoid the collision.

2.4 EDCA

In IEEE 802.11e, hybrid coordination function (HCF) is defined as the MAC scheme [3, 4]. 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,

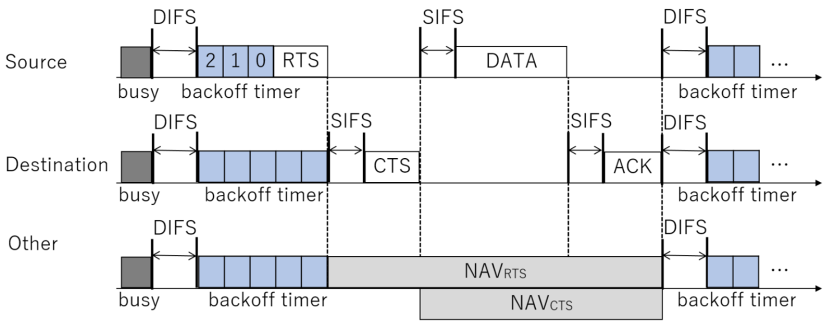


Figure 2.3: RTS/CTS/DATA/ACK mechanism

Table 2.2: Each AC priority

AC	AIFSN	CW_{min}	CW_{max}	TXOP	priority
AC[VO]	2	7	15	3264 μ sec	Highest
AC[VI]	2	15	31	6016 μ sec	
AC[BE]	3	31	1023	0	
AC[BK]	7	31	1023	0	Lowest

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. The Table.2.2 shows the AIFSN (AIFS Number), CW_{min}, CW_{max} and TXOP of each AC in the case that IEEE 802.11b is adopted as the wireless medium. Using AIFSN of each AC, the AIFS is calculated as

$$AIFS[AC] = SIFS + AIFSN[AC] * t_{slt} \tag{2.2}$$

where t_{slt} is time slot. According to the priority of the each AC, the waiting duration for the transmission is changed as shown in Table.2.2.

2.5 Multi-hop wireless networks

In multi-hop wireless networks, the transmission between two nodes may require more than one hop. Thus, the throughput decreases rapidly due

Table 2.3: Path loss exponent

Network environment	Path loss exponent
Free Space	2
Urban Area	$2.7 \sim 3.5$
Shadowed Urban Area	$3 \sim 5$

to the hidden node problem, exposed node problem and receiver blocking problem. For analyzing three problems, the carrier sensing range, the interference range and the transmission range are important. First, the following subsections explain the sensing area and then introduce the three problems.

2.5.1 Sensing area

The carrier sensing range R_{cs} is the range that the received signal power is larger than the carrier sensing threshold, that is, the minimum range allowed two concurrent transmitters. Otherwise, the node which received the signal is idle and the received signal is considered as noise. The R_{cs} depends on the carrier sensing threshold.

The interference range R_i is the range that the receiving node is interfered with an unrelated transmitter. The collision is occurred in the receiving node when a node within R_i of the receiving node transmits a packet. The R_i is the explained as

$$R_i = r \cdot SINR^{\frac{1}{\gamma}} \tag{2.3}$$

where r is the distance between the transmitter and the receiver, $SINR$ is the Signal to Interference plus Noise Ratio and γ is the path loss exponent. The Table.2.3 shows the path loss exponent according to network environment [5]. In simulation, this thesis needs to set the value of the path loss exponent according to assumed network environment.

The transmission range T_{tx} is the range that the transmitter transmits a packet successfully if the interference from other nodes is not occurred. The T_{tx} largely depends on the transmission power and the radio propagation properties (e.g., antenna gain).

2.5.2 Hidden node problem

The hidden node problem occurs that nodes can not hear each other. The Fig.2.4 shows the hidden node problem. Node 1 transmits a packet to node 2. Then node 3 can not hear that because node 1 is out of carrier sensing range of node3. The collision occurs when node 3 transmits a packet to node 2 during transmission of node 1.

The Fig.2.5 shows the hidden node range of node 1 and node 2. The hidden node area of each node is gray area in Fig.2.5. I denote by $H'(r)$

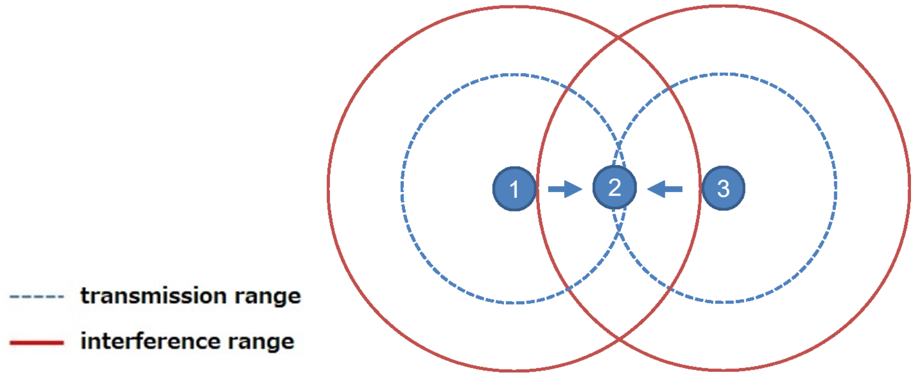


Figure 2.4: Hidden node problem

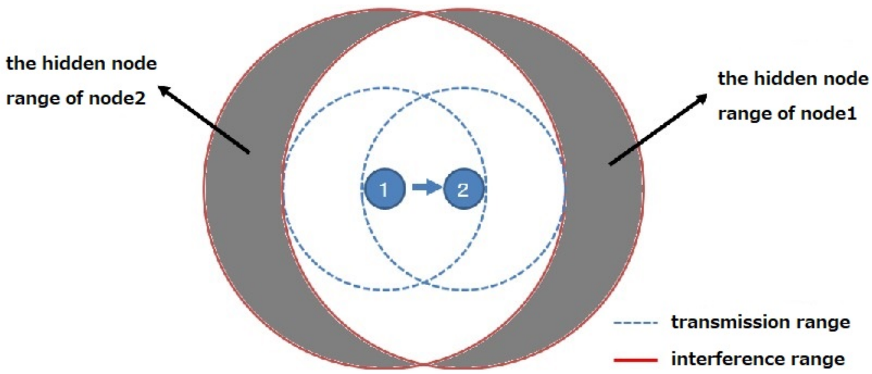


Figure 2.5: The hidden node range

and r the hidden node area and the distance between node 1 and node 2, respectively. The $H'(r)$ can be expressed

$$H'(r) = \pi R_{cs}^2 - 2R_{cs}^2 \left[arccos \frac{r}{2R_{cs}} - \frac{r}{2R_{cs}} \sqrt{1 - (\frac{r}{2R_{cs}})^2} \right]. \tag{2.4}$$

2.5.3 Exposed node problem

The exposed node is in the range which is inside of R_{cs} of the transmitter and outside of R_{cs} of the receiver. The exposed node is the gray area in Fig.2.6. While node 1 transmits a packet to node 2, node 3 cannot transmit a packet to node 4 since node 3 hears the transmission of node 1 and defers own transmission. Also, While node 1 transmits a packet to node 2, node 5 cannot hear the response for the RTS/DATA since node 6 is blocked by the transmission of node 1.

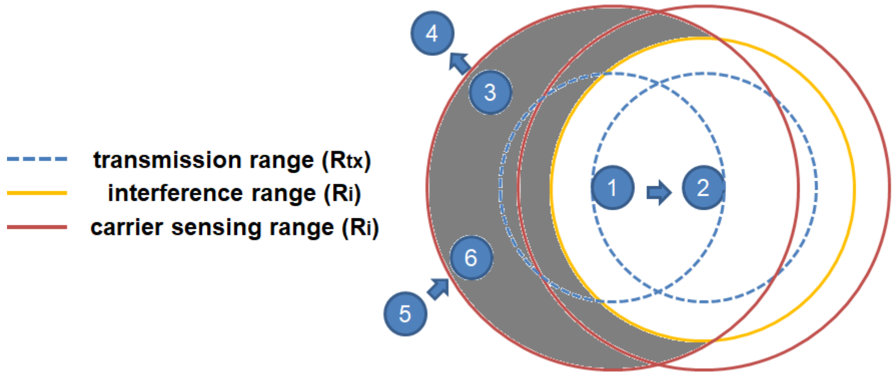


Figure 2.6: The exposed node problem

2.5.4 Receiver blocking problem

The receiver blocking problem is occurred when a node cannot response for the RTS/DATA since the receiver is blocked by the transmission of other node. In Fig.2.7, node 1 transmits the RTS packet to node 2, node 3 is blocked because node 3 hears the RTS packet and waits for the NAV duration. Node 4 transmits the RTS packet to node 3, however, node 4 hear the response for the RTS packet since node 3 is blocked. Additionally, node 5 is blocked because node 4 transmits the RTS packet. The neighbors of a blocked node are unaware of the fact that the node is blocked, with result that the neighbor of a blocked node transmits a packet to a blocked node and cannot receive the response.

The blocked node need not be a hidden or an exposed node. For example, in Fig.2.7, node 3 can receive both the RTS packet and the CTS packet. Thus, node 3 is neither a hidden nor exposed node and is blocked node.

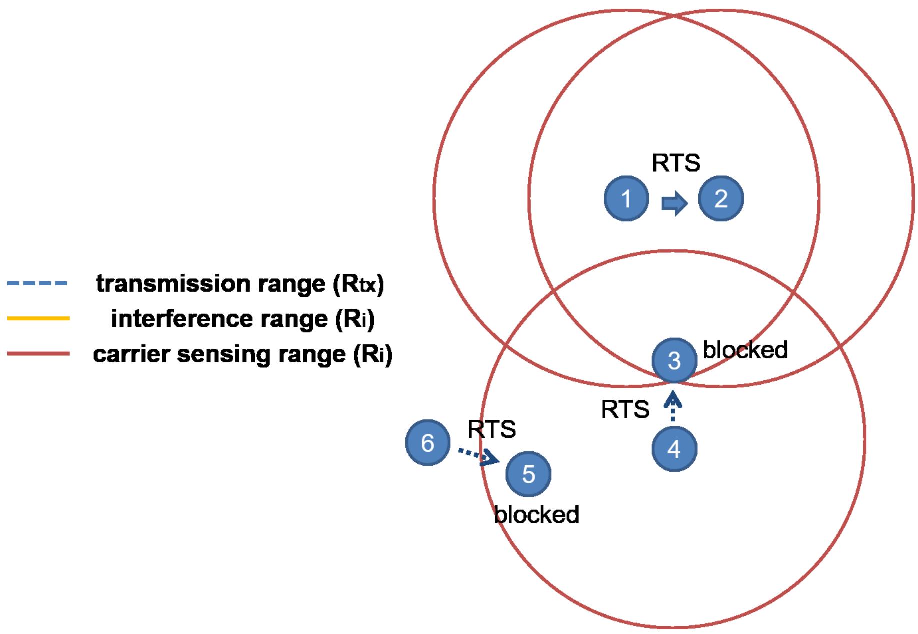


Figure 2.7: The receiver blocking problem

Chapter 3

Improving the throughput and the fairness in single-hop

WLANs have become increasingly popular and widely deployed. Due to inherent simplicity and flexibility, DCF is preferred in the case of no base station such as vehicle to vehicle communications. Since all the nodes share a common wireless channel with limited bandwidth in WLANs, it is highly desirable that an efficient and fair MAC protocol is employed. However, for the DCF, there is much room for improvement in terms of both efficiency and fairness. As demonstrated in [6], the fairness as well as throughput 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 DCF, estimating the number of nodes is difficult because each node can reach or leave the network freely. For that reason, many researches have avoided estimating the number of nodes. In [7], although the number of nodes is estimated, however, it is complicated and it takes time to carry out this procedure. In [8] and [9], these schemes observe the average idle interval, and adjust the CW (Contention Window) in order to obtain a higher throughput. However these schemes do not estimate the number of nodes and have an issue in that the variation in CW of each node 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 this is still not enough. In this thesis, focusing on MAC protocol, I propose a novel protocol that each node estimates the number of nodes in a network with short convergence time and no overhead traffic burden added to the network through observing the channel, and nodes dynamically optimize their backoff process to achieve high throughput and satisfactory fairness.

The remainder of this chapter is organized as follows. In Section 3.1, I explain the background of this research. The Section 3.2 sorts out the

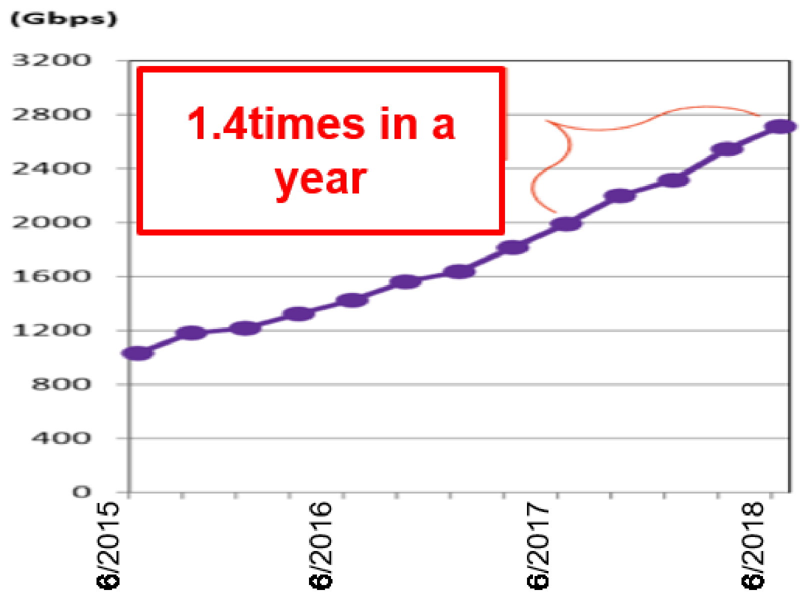


Figure 3.1: The monthly average mobile communication traffic in Japan

problems in term of throughput and fairness. I introduce the related works that resolve these problems and improve throughput or fairness in Section 3.3. These related works are better than the conventional method in term of throughput or fairness, but not enough. In Section 3.4, I elaborate on our key idea and the theoretical analysis for improvement. Then I present in detail our proposed Optimizing Backoff by dynamically Estimating Number of nodes OBEN scheme. Section 3.5 gives a performance evaluation and discusses the simulation results. Finally, concluding remarks are given in Section 3.6.

3.1 Background

WLANs have become increasingly popular and widely deployed. The Fig. 3.1 shows the monthly average mobile communication traffic (not include voice traffic) in Japan [11]. The monthly average mobile communication traffic increases year by year and is about 2000Gbps in 6/2017. It has increased 1.4 times in the last year. Also, the Fig. 3.2 shows the number of Internet of Things (IoT) connected devices worldwide from 2015 to 2025 [12]. For 2025, the IoT devices is forecast to grow to almost 75 billion worldwide. Since the traffic and the number of nodes are expected to increase, a correspoinding method is required.

WLANs have two channel access method, DCF and PCF, as shown in Ta-

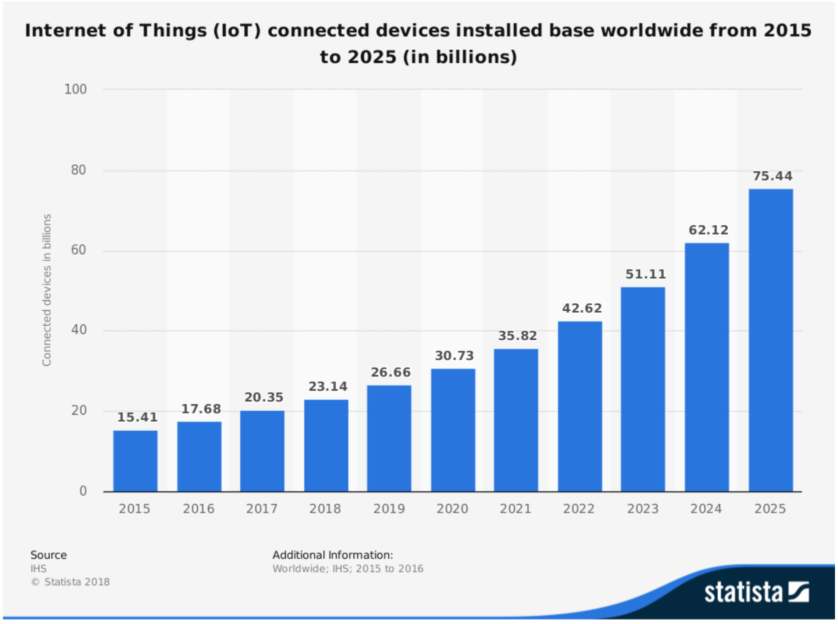


Figure 3.2: IoT connected devices installed base worldwide from 2015 to 2025

ble 3.1. The access method PCF need the infrastructure but the throughput in high traffic and the fairness are high. By contrast, in DCF, the throughput in high traffic and the fairness is low since the infrastructure does not need. In view of future wireless communication traffic demands, the access method DCF that can configure the network flexibly becomes necessary. It is highly desirable that an efficient and fair DCF. Thus, this thesis focuses on DCF.

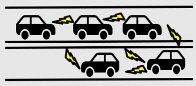
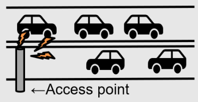
3.2 Problems of the conventional method

There are two problems in the conventional communication method DCF, therefore, the throughput and the fairness become low. In following, I give the problems of the conventional method.

- The throughput decreases when the number of nodes increases.
- The variation of the CW is large.

The node having packets for transmission senses the channel first. When the channel is idle for DIFS, the node carries out the backoff process. The node selects the backoff counter uniformly in the range $[0, CW]$ and begins to decrease the backoff counter bye one for each idle time slot. The node can

Table 3.1: Access method in IEEE 802.11

Access method	DCF (Distibuted Coordination Function)	PCF (Point Coordination Function)
Network configuration		
Infrastructure	Good (not need)	Bad (need)
Throughput in high traffic	Bad (low)	Good (high)
Fairness	Bad (low)	Good (high)

transmit packets when the backoff counter is 0. In the case of collision, the node doubles its CW until reaching a maximum value CW_{max}, chooses a new backoff counter and starts the backoff process again. In the case of successful transmission, the node resets its CW to CW_{min}. Due to this algorithm, the throughput decreases when the number of nodes increases, as shown in Fig.3.3. There is the optimal CW that can maximize the throughput according to the number of nodes [13]. The node takes time until it changes from the CW_{min} to the around optimal CW and repeats many times. This problem is remarkable when the number of nodes increases.

In addition, The variation of the CW is large. The Fig.3.4 shows the variation of the CW. When the variation of the CW is large, a large difference occurs in the transmission between nodes. For this reason, the fairness decreases and the jitter is large. Therefore, the above problems need to be resolved.

3.3 Related works

Considerable research efforts have been expended on either theoretical analysis or throughput improvement ([6, 14, 15, 16, 17, 18, 19, 13, 20, 21, 22, 23, 24]). In [13], Cali et al. derived an optimal CW that can maximize the throughput. With the optimal CW, a backoff algorithm is proposed. Also, the method for estimating the number of nodes is proposed, however, this is complicated and it takes time to estimate the number of nodes, which is short of adaptivity to network changes. In [6], Bianchi used a Kim and Hou developed a model-based frame scheduling algorithm to improve the protocol capacity of the 802.11 [24]. In this scheme, each node sets its backoff timer in the same way as in the IEEE 802.11; however, when the backoff timer reaches zero, it waits for an additional amount of time before accessing the medium. Though this scheme improves the efficiency of medium access, the calculation of the additional time is complicated since the number of ac-

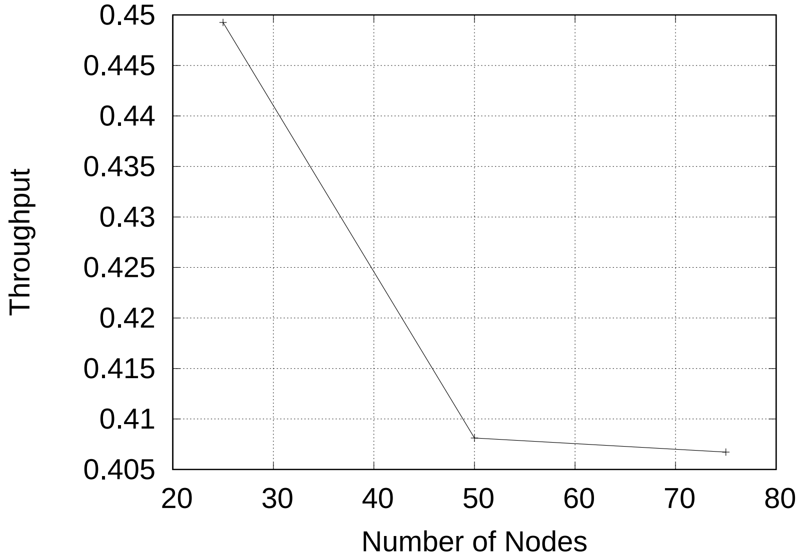


Figure 3.3: Monotone function $f_{idl}(n)$ when the real value of n is 50

tive nodes must be accurately estimated. In [14, 15, 16], the works improve throughput and fairness for multi-rate traffic in the saturated case. However, in [14], the MAC frame header contains the additional information, and the throughput becomes low in the non-saturated case. These works [15, 16] assume that the system environment is coordinated by an access point (AP). That is, they do not work without AP. In our previous study, a novel MAC protocol OSRAP was proposed [25], which can achieve a low packet delay and higher throughput. However, it needs to select a node as the head, which is not a perfect distributed protocol. In Idle Sense [8] and DOB [9], each node observes the average idle interval between two transmissions, and selects optimal CW according to the average idle interval to obtains high throughtput. However, the works cannot avoid the multiple transmissions from other nodes between two transmissions of a node and fairness is degraded. In AMOCW [10], based on Idle Sense, changes the method of collecting the average idle interval for preventing the multiple transmissions. With throughput like Idle Sense, AMOCW obtains fairness better than Idle Sense but not enough due to using AIMD (Additive Increase Multiplicative Decrease) algorithm. The fairness is another important issue in MAC protocol design [26].

Here, I propose a novel protocol OBEN to improve both throughput and fairness. OBEN estimates the number of active nodes in a simple but effective way instead of the complicated method used before. Compared to the methods in [8, 9, 10], since each node in OBEN can correctly estimate the

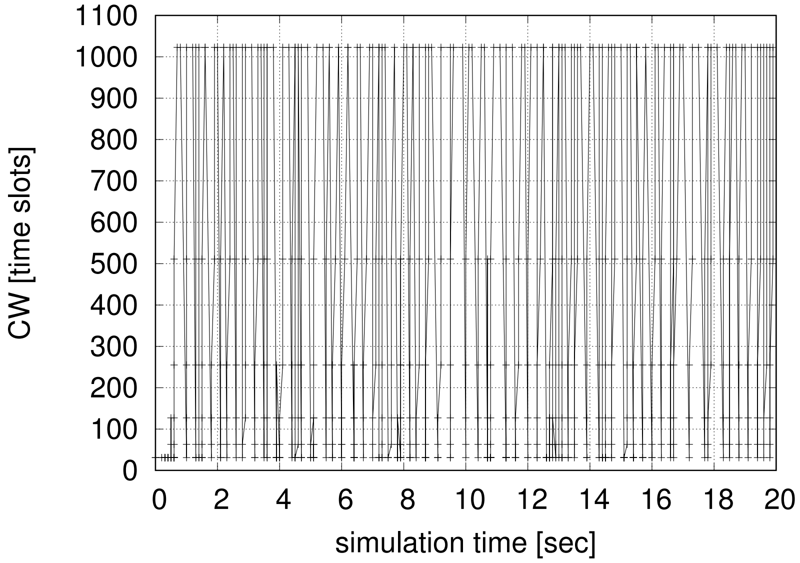


Figure 3.4: The variation of the *CW*

number of nodes and keep its *CW* close to the same optimal value, OBEN can maintain fairness and keep the network operating with less fluctuation.

3.4 Analysis and the proposal of optimizing backoff by dynamically estimating the number of nodes

3.4.1 Motivation

In the IEEE 802.11 MAC, an appropriate *CW* is the key to providing throughput and fairness. A small *CW* results in a high collision probability, whereas a large *CW* results in wasted idle time slots. In [13], Cali et al. showed that given the number of active nodes, there exists an optimal *CW* that leads to the theoretical throughput limit and when the number of active nodes changes, so does this optimal *CW*. Since in practice, the number of active nodes always changes, to let each node attain and keep using the corresponding optimal *CW* requires the estimation of the number of active nodes. However, previous methods for on line estimation and convergence time for all nodes are complicated since to estimate the exact number of nodes takes a long time. To get around this difficulty, this thesis is thus motivated to find another effective method that leads us to the optimal *CW* and hence the maximal throughput.

I expect the improvement protocol to have several characteristics as follows

- no added overhead of measurement for understanding network situation.
- being concise and effective.
- achieving both high throughput and comparatively good fairness.

One problem for DCF is that when traffic increases throughput will reach the upper bound and the maximum throughput is lower than PCF, so added overhead of measurement is not expected. In the situation where there is limited computation resource of a mobile node and a changing network, a concise and effective protocol is desirable. For vehicle to vehicle communication, real time data needs to be sent with little delay and each vehicle needs a minimum data rate for urgent data transmission even in a saturation case, so both high throughput and comparatively good fairness are required. I try to get the necessary information for optimizing transmission in a wireless network by listening to the wireless channel, which is simple since the DCF is in fact built on the basis of physical and virtual carrier sensing mechanisms. As shown below, I obtain the necessary indexes to give an improved protocol through listening to the wireless channel.

multi-hop wireless networks are necessary for systems such as vehicle to vehicle communications. The DCF is preferred since it can work without AP. In multi-hop wireless networks, the throughput becomes low because of hidden terminal problems and a multi-channel is an effective method in that a group of nodes communicates with a single frequency channel.

This chapter assumes that the nodes of network communicate with each other using a certain frequency channel in one hop area, while leaving the task of how to arrange frequency channel to each group as the next work. The study about multi-hop wireless networks is described in chapter5. Here, I try to give an effective protocol with high throughput and good fairness for one hop area.

In the following, I derive the relationship between the average idle interval and the throughput through analysis. Using the relationship, nodes can obtain the optimal CW and achieve the high throughput and the good fairness. For the purpose of simplicity, this thesis assumes the frame length is constant and give the simulation results with different packet sizes.

3.4.2 Analytical Study

In the IEEE 802.11 MAC, an appropriate CW is the key to providing throughput and fairness. In [13], the DCF is analyzed based on the 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 OBEN would enable all the nodes to settle on a quasi-stable CW shortly after the network is put into operation, for simplicity this thesis assumes that all the nodes use the same and fixed CW. Consequently, I have

$$p = \frac{2}{CW+1} \tag{3.1}$$

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

$$\begin{aligned} P_{idl} &= (1-p)^n \\ P_s &= np(1-p)^{n-1} \\ P_{col} &= 1 - P_{idl} - P_s \end{aligned} \tag{3.2}$$

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

$$\rho = \frac{TP_S}{t_{slt}P_{idl} + T_{col}P_{col} + T_{tx}P_s} \tag{3.3}$$

where T is the transmission time of one packet, t_{slt} is slot time, T_{tx} is the successful transmission duration and T_{col} is the collision duration. Our aim is to maximize throughput shown in equation (5.11). To this end, I need to obtain the optimal CW according to the network condition such as the number of nodes. In the following, I give the method for estimating the number of nodes on line by three parameters P_{idl}, P_s and P_{col} which can be obtained directly by listening to the channel for a certain interval. Then, using obtained P_{idl}, P_s and P_{col}, I give the method for maximizing the throughput dynamically. Calculating the number of nodes directly by equation (3.2) is inefficient and unrealistic. Here, I uses a simple and effective method which is suitable for real time estimating. From equation (3.2), I 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 following,

$$P_{idl} = (1 - \frac{P_s}{nP_{idl} + P_s})^n. \tag{3.4}$$

Let $f_{idl}(n) = (1 - \frac{P_s}{nP_{idl}+P_s})^n$, where P_{idl}, P_s and P_{col} are known parameters and n is the unknown parameter that needs to be estimated. Then when

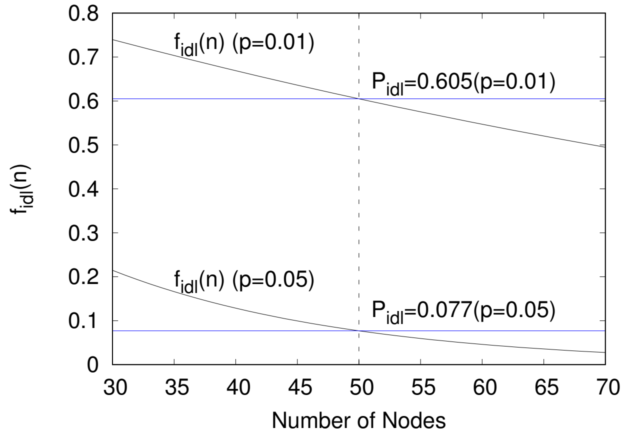


Figure 3.5: Monotone function $f_{idl}(n)$ when the real value of n is 50

$f_{idl}(n_0) = P_{idl}$, n_0 is the needed value. I find that $f_{idl}(n)$ is the monotone function. I take the derivative of f_{idl} with respect to n, and let $\frac{\mathrm{d}f}{\mathrm{d}n} = [\ln(1 - \frac{P_s}{nP_{idl}+P_s}) + \frac{P_s}{nP_{idl}+P_s}](1 - \frac{P_s}{nP_{idl}+P_s})^n$. 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 $\frac{\mathrm{d}f}{\mathrm{d}n}$ becomes $\ln(1-x)+x$ which changes from 0 to $-\infty$ when x changes from 0 to 1. So, it can be understood that $\frac{\mathrm{d}f}{\mathrm{d}n}$ is not plus.

I can estimate the number of nodes by the simple calculation method, without solving a complicated equation. As shown in Fig. 3.5, the monotone function $f_{idl}(n)$ always decreases as the number of nodes is increasing. 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 number of nodes deployed in real network.

The above characteristic is favorable for estimating the 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 $f_{idl}(n_{try1}) > P_{idl}$, I should set $n_{try2} = [n_{try1}+n_{max}]/2$. Otherwise, I should set $n_{try2} = [n_{try1}+0]/2$ for the following calculation. Obviously, this method is simple and effective. For example, when $n_{max} = 100$, nodes just need to calculate four times to estimate n in the worst case with maximum error 3. In the following, I present the condition of high throughput. And then, I give the method of how to dynamically tune CW to enhance throughput and fairness. The average idle slot interval is denoted by L_{idl}, it can be expressed as

$$L_{idl} = \frac{P_{idl}}{1 - P_{idl}}. \tag{3.5}$$

With equation (5.1), (3.2) and (5.14), this equation can be further written as

$$\begin{aligned} L_{idl} &= \frac{1}{(1+2/(CW-1))^n - 1} \\ &= \frac{1}{n\frac{2}{CW-1}+...+\binom{n}{i}(\frac{2}{CW-1})^{n-i}+...+(\frac{2}{CW-1})^n}. \end{aligned} \tag{3.6}$$

I can simplify the equation (3.6) as

$$L_{idl} = \frac{CW-1}{2n}. \tag{3.7}$$

I can obtain the equation (3.7) 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 is large enough for the approximation $L_{idl} = (CW-1)/(2n)$ in our OBEN, which is also verified through simulations.

With Equation (5.11) and (3.7), thinking IEEE 802.11b, I can express the throughput as a function of L_{idl} with SIFS=10s, DIFS=28s, ACK=304bits and time slot=9s, as shown in Fig. 4.1. From the figure, first, I find that every curve follows the same pattern; namely, as the average idle slot interval L_{idl} increases, the throughput first rises quickly, and then decreases relatively slowly after reaching its peak. Second, although the optimal value of L_{idl} that maximizes throughput is different in cases 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 active nodes. Therefore, L_{idl} is a suitable measure that indicates the network throughput. If nodes can estimate the number of nodes correctly, they can set the optimal CW by L_{idl} and n to achieve high throughput.

In Fig. 4.1, 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 $Lidl = [4, 6]$. From the above equation (3.7), according to the number of nodes, each node can set the optimal CW that $CW = 2nL_{idl} + 1$. Since I am interested in tuning the network to obtain maximal throughput, given the linear relationship, I 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 so that the throughput of the network is maximized.

3.4.3 OBEN Scheme

As mentioned above, I can obtain the optimal CW by Eq. (3.7) by using the estimated number of active nodes. Hence, each node can adjust its CW dynamiclly and tune the network to deliver high throughput. To obtain the

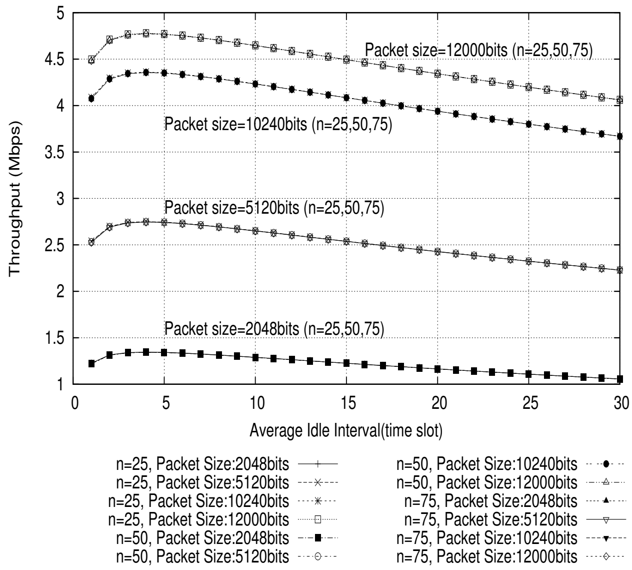


Figure 3.6: Throughput with average idle slot interval

P_{idl}, P_s and P_{col}, I can count the number of idle slots (C_{idl}), collisions (C_{col}) and successful transmissions (C_s) individually. To avoid occasional cases, C_{idl}, C_{col} and C_s are expected to be measured in resetting the counters before a transmission. The P_{idl}, P_s and P_{col} can be calculated as

$$\begin{aligned} P_{idl} &= \frac{C_{idl}}{C_{idl} + C_s + C_{col}} \\ P_s &= \frac{C_s}{C_{idl} + C_s + C_{col}} \\ P_{col} &= \frac{C_{col}}{C_{idl} + C_s + C_{col}} \end{aligned} \tag{3.8}$$

Since different MAC protocols have different definitions of time interval such as DIFS, SIFS, C_{idl} may need to be adjusted. A node calculates the CW before packet transmissions. After new CW (newCW) is obtained, the CW can be updated as

$$CW = \beta \cdot CW + (1 - \beta) \cdot newCW \tag{3.9}$$

where β is a smoothing factor with the range of [0,1]. Fig. 3.7 shows the sizes of CW of a node with simulation time when the β is changed. The higher β leads to stability but maybe reduces adaptivity to network changes such as traffic and active nodes. In OBEN, the sizes of CW are largely varied by little changes in the probabilities of idle, successful transmission and collision, which results in degraded throughput and fairness. For minimizing

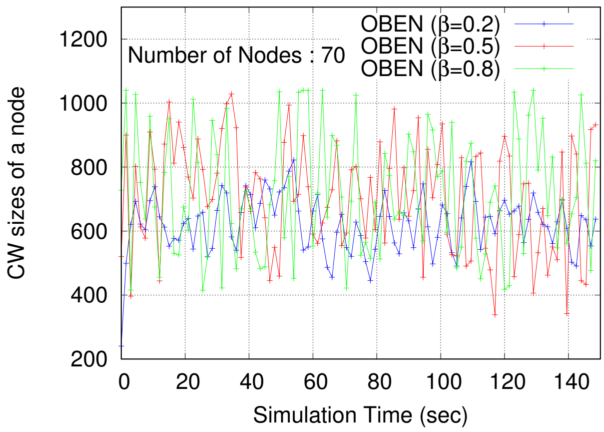


Figure 3.7: CW sizes with simulation time when the β is changed

the variation of CW and adjusting the changes in the number of nodes, I set $\beta = 0.8$ in simulation results in the next section. In the following, I give the tuning algorithm.

1. A node, say Node A, begins listening to a 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, it calculates the optimal CW as a new CW and resets CW according to Eq. (3.9).

3. It resets counting events of idle slot, successful transmission and collision.

The certain number of packet transmissions needs to be set appropriately. When the number is small, CW changes rapidly with network changes. In contrast, if the number is large, the network can have higher stability but is short of adaptivity. In the following simulation, I set a certain number as 2. Ideally, each node should have the same CW when the network enters into a steady state in saturated case; in reality, each node sets its CW around the optimal value. Using this method, high throughput and good fairness are achieved, which can be found in the following simulations.

3.5 Performance evaluations

In this section, I focus on evaluating the performance of our OBEN through simulations, which are carried out on OPNET Modeler [27]. OPNET Modeler, currently known as Riberbed Moder [28], is a commercial simulator that can be used for a fee. It can perform advanced protocol model development and flexible scenario creation. For comparison purposes, I also present the simulation results for the IEEE 802.11b DCF. In all the simu-

Table 3.2: Network configuration

Parameter	Value
$MinCW$	31
$MaxCW$	1023
SIFS	10 μsec
DIFS	50 μsec
Slot time	20 μsec
Bit rate	11 Mbps

Table 3.3: Backoff parameters

Parameter	Value
L_{idl}	5
β	0.8
Maximum number of nodes	100

lations, I consider the MAC scheme, where RTS/CTS mechanism is used. Generally, OBEN works for all IEEE 802.11 family. Though many improved IEEE 802.11 MAC protocols have been proposed, the evaluation condition and environment are different. Here, I compare our proposed OBEN with AMOCW proposed in [10] which achieved the best results and Idle Sense [8]. In view of the fact that the performance of IEEE 802.11 standard is well known, in this section, I also use IEEE 802.11b as the standard reference. The related parameters of IEEE 802.11b are shown in TABLE 5.1 and the OBEN-specific parameters in TABLE 3.3. The L_{idl} is 5 for obtaining high throughput as shown in Fig. 4.1.

I assume that network nodes are distributed at random in a round area with a 200 meter radius and that all nodes are in the communication range. Without a specific application, I assume that each node generates traffic according to a Poisson process with the same arrival rate. Since I focus on throughput in the saturated case, the throughputs with different arrival distributions are slightly different in the border around the non-saturated and saturated case but the effects of an arrival distribution are extremely small. In the fully non-saturated case and saturated case, the throughputs are almost similar. Each node selects another node at random as a receiver. The arrival rate is kept increasing until the network is saturated. As shown below, OBEN exhibits a better performance.

3.5.1 Throughput

Firstly, I give the throughput of four schemes, i.e., OBEN, AMOCW, Idle Sense and DCF of IEEE 802.11b under different offered loads and packetsizes. Fig. 3.8 shows the throughput results with a different number of

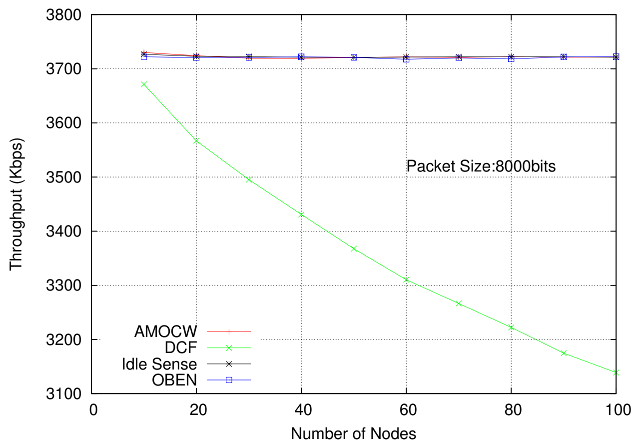


Figure 3.8: Throughput with node numbers

Table 3.4: Throughput (Kbps) with node numbers

N	AMOCW	DCF	Idle Sense	OBEN
10	3730	3671	3727	3722
20	3724	3567	3723	3721
30	3720	3495	3723	3721
40	3719	3431	3721	3722
50	3721	3368	3721	3721
60	3722	3310	3722	3718
70	3721	3266	3722	3720
80	3723	3222	3722	3718
90	3721	3175	3722	3722
100	3722	3139	3721	3723

nodes. The packet size is the size of payload data at MAC layer and does not include MAC overhead, which is one reason that the simulation results are lower than the theoretical values. The throughput is the total data traffic successfully received.

The throughput of IEEE 802.11 DCF decreases with the number of nodes increasing. When the number of nodes changes from 10 to 100, the throughput of IEEE 802.11 DCF falls from 3.68Mbps to 3.12Mbps, about 18% down. On the contrary, our proposal OBEN, Idle Sense and AMOCW have almost no changes. The throughput of OBEN is almost same as that of Idle Sense and AMOCW, that the three lines of OBEN, Idle Sense and AMOCW overlap each other in the figure. The detail can be found in the Table 3.4 with throughput data. While achieving as high throughput as AMOCW, OBEN has a better fairness, which will be shown in the next section.

3.5.2 Variation of CW and Fairness

Many researches deal with the fairness of networks. For different applications, there are different requests. Here, I omit the detail and just evaluate this item in way of an intuitive awareness. IEEE 802.11 applies an exponentiation backoff algorithm which can disperse retransmission timing among collision nodes. However, some nodes may defer time too long so that they cannot transmit for a long interval, which results in poor fairness as occurred in AMOCW and Idle Sense. I can evaluate the fairness of OBEN with AMOCW through the observation of CW variation in the saturation case. Fig. 3.9 shows the instantaneous value of CW of a node in simulation. At the beginning, 20 active nodes compete for the channel. After 50 seconds, 40 nodes start competing for the channel. Then, the 40 nodes leave after 100 seconds. From Fig. 3.9, OBEN is coincided with the analysis results and has good scalability in runtime. In contrast, CWs of AMOCW, Idle Sense and DCF vary intensely when the number of nodes increases quickly, which means a big change of the transmission interval in view of the time dimension and this results in poor fairness and high jitter. Fig. 3.10 shows the instantaneous value of CW and the retransmission attempts of a node. OBEN has a small variation of CW and the number of retransmission attemps because OBEN always obtains CW around the optimal value. In contrast, in AMOCW, the variation of CW is large, which causes many retransmission attempts and decreases fairness as described below.

To evaluate the fairness of OBEN, I adopt the following Fairness Index (FI) [29] that is commonly accepted:

$$FI = \frac{(\sum_{i=1} T_i/\phi_i)^2}{n\sum_{i=1}(T_i/\phi_i)^2} \tag{3.10}$$

where T_i is throughput of flow i, ϕ_i is the weight of flow i (normalized throughput requested by each node). Here, I assume all nodes have the same weight in simulation. According to equation (4.7), $FI \leq 1$, where the equation holds only when all T_i/ϕ_i are equal. Normally, a higher FI means a better fairness.

Figure 5.9 shows the results with a different number of nodes from 10 to 100, in which the results of OBEN, AMOCW, Idle Sense and IEEE 802.11 DCF are put together for comparison. From the figure, I can see that our proposal OBEN has the best fairness among the four protocols. In particular, when the number of nodes increases, the fairness of OBEN has no obvious changes. On the other hand, Idle Sense degrades fairness heavily and becomes lower than DCF from 50 nodes, which results from each node of Idle Sense not knowing the correct CW to which it should set and it just increases or decreases CW according to the common channel situation indicated by the average idle interval. Thus, a lack of balance occurs among nodes in the network. The same tendency also can be found for AMOCW

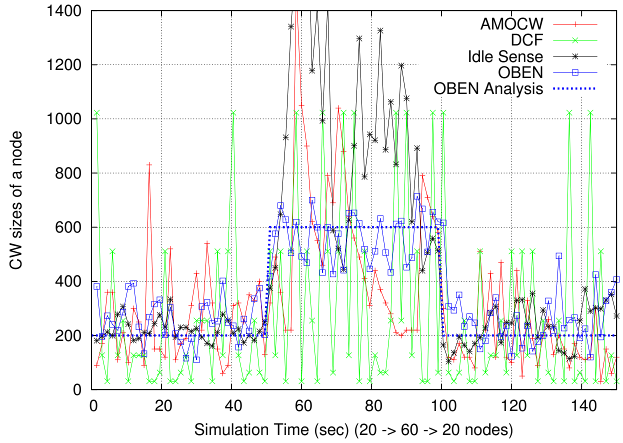


Figure 3.9: *CW* sizes of a node with simulation time

except that the fairness is improved. For Idle Sense and AMOCW, the fairness changes periodically, which is thought to be the result of AIMD algorithm used in Idle Sense and AMOCW. From the figure, I can see that the fairness of OBEN is dramatically enhanced.

3.6 Conclusions

In OBEN, nodes just need to confirm if the media is busy or idle to obtain the number of idle slots, successful transmissions and collisions through listening to a wireless channel without added overhead. And then using a simple and effective method, OBEN estimates the number of nodes to set an optimal CW. Meanwhile, though all the nodes may not have the same CW, occasionally, each node can adjust its CW rapidly and keeps close to the optimal value, which means they will fairly share the common wireless channel. This leads to good fairness.

Through both analysis and simulation, our scheme has the following advantages. First, the method of estimating the number of active nodes of a channel is simple and effective for each node to grasp the network traffic situation. In addition, the average idle length is insensitive to the change in packet length or the number of active nodes. Each node can adjust its backoff process simply, avoiding complex calculations. Second, compared with the Idle Sense and AMOCW, OBEN achieves better fairness with almost the same throughput.

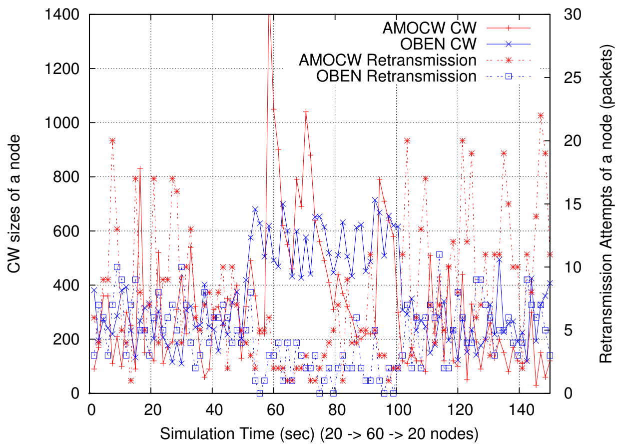


Figure 3.10: *CW* sizes and retransmission attempts of a node with simulation time

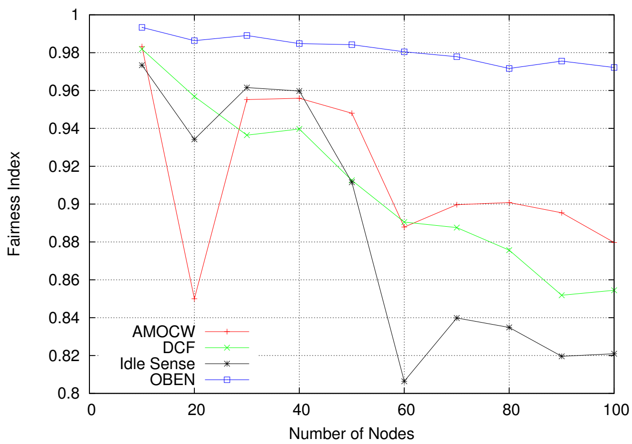


Figure 3.11: Fairness Index

Chapter 4

Improving the throughput and the fairness in single-hop with QoS

The Chapter 3 proposed the new MAC protocol OBEN. Whereas, OBEN does not take QoS into account. The real time traffic need to be provided with the required throughput and delay guarantees. According to the kind of traffic, the node must control the transmission opportunity. Thus, this chapter proposes a novel MAC protocol scheme that Optimizing Backoff with better QoS, named as OBQ. OBQ, based on OBEN, can improve the throughput and the fairness with good QoS.

The remainder of this chapter is organized as follows. The Section 4.1 describes the problems of the conventional method. I introduce the related work in Section 4.2 I elaborate on our key idea and the theoretical analysis for improvement in Section 4.3. Then I present our proposed scheme OBQ in detail. Section 4.4 gives performance evaluation and the discussions on the simulation results. Finally, concluding remarks are given in Section 4.5.

4.1 Problems of the conventional method

IEEE 802.11e EDCA, based on IEEE 802.11 DCF, supports QoS for traffics with different priorities. In EDCA, there are three problems as follows.

- The throughput decreases when the number of nodes increases.
- The variation of the CW is large.
- QoS is not enough.

EDCA also has similar problems as DCF. First and second, this thesis already explained in Chapter 3. Third, 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 [3, 4]. Consequently, in this chapter, I can solve these problems and enhance the throughput and the fairness with good QoS.

4.2 Related works

The related works [30, 31, 32, 33, 34, 35, 36, 37, 38, 39] proposed several schemes to improve EDCA. In [30], a super slot allocation mechanism is proposed by integrating three time slots into a supper slot, each slot in the super slot is allocated to a particular AC(access category) according to its priority to reduce collisions. In [33], 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 [34], when the traffic load is heavy the nodes suspend some transmissions. Although, in [30, 31, 32, 33, 34], when a collision is occurred, CW is doubled like conventional method, which leads to deteriorate fairness among nodes in the same environment. In [37], considering MAC queue dynamics of each AC and QoS requirements, each node adjusts the delay-based CW. In [39], its proposed method provides real time traffic with the required throughput and delay guarantees. However, the above works do not take fairness into account. This chapter aims to enhance throughput, fairness and QoS for EDCA at the same time by solving the problems of conventional method and estimating the number of nodes briefly and dynamically. I use the method in OBEN, as described in Chapter 3, to tune CW according to each priority to achieve good performance. Then, I propose a novel MAC scheme that Optimizing Backoff with better QoS, named as OBQ.

4.3 Analysis and the proposal of optimizing backoff by dynamically estimating number of nodes

As shown in previous research works, the network performance depends principally on CW and backoff strategy. From now, firstly I 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 I can determine CW for each AC in a node according to its CW_{op} and QoS requirement.

4.3.1 Optimal Backoff

The analysis in OBQ is similar to OBEN because OBQ is based on OBEN. The transmission probability p is shown in equation (5.1) and the probabilities of idle P_{idl}, successful transmission P_s and collision P_{col} are shown in equation (3.2). By using these equations, the throughput is expressed as

$$\rho = \frac{TP_s}{t_{slt}P_{idl} + T_{col}P_{col} + T_{tx}P_s} \tag{4.1}$$

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], I take ACs as AC[VO], AC[VI] and AC[BE] in the analysis. OBQ controls 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 η_{VO}, η_{VI} and η_{BE}, respectively, which satisfy $\eta_{VO}+\eta_{VI}+\eta_{BE} = 1$. Consequently, T_{col}, T_{tx} and T can be expressed as

$$\begin{aligned} T_{col} &= T_{col\_VO} \cdot \eta_{VO} + T_{col\_VI} \cdot \eta_{VI} \\ &\quad + T_{col\_BE} \cdot \eta_{BE} \\ T_{tx} &= T_{tx\_VO} \cdot \eta_{VO} + T_{tx\_VI} \cdot \eta_{VI} \\ &\quad + T_{tx\_BE} \cdot \eta_{BE} \\ T &= T_{\_VO} \cdot \eta_{VO} + T_{\_VI} \cdot \eta_{VI} + T_{\_BE} \cdot \eta_{BE} \end{aligned} \tag{4.2}$$

where

$$\begin{aligned} T_{col\_VO} &= T_{\_VO} + EIFS - DIFS \\ &\quad + AIFS[VO] + \tau \\ T_{tx\_VO} &= (T_{\_VO} + SIFS \cdot 2 + ACK + 2\tau) \\ &\quad \cdot t_{n\_VO} - SIFS + AIFS[VO] \\ T_{\_VO} &= (T_{data} + T_{head}) \cdot t_{n\_VO} \end{aligned} \tag{4.3}$$

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. τ 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 equation (4.1).

Each node estimates the number of nodes and calculates the optimal CW in the same method as OBEN. The average idle slot interval L_{idl} is expressed as equation (5.14). With equations (4.1) and (5.14), I can express

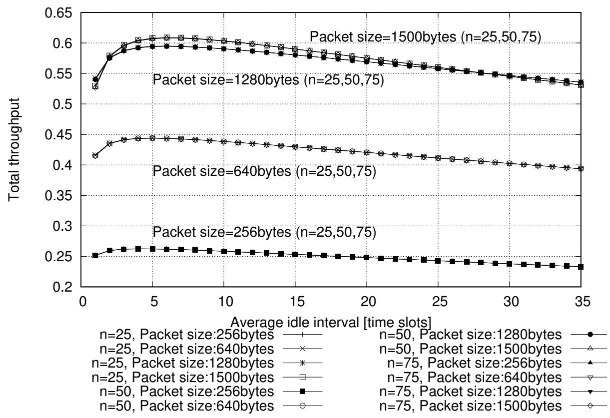


Figure 4.1: Throughput vs. average idle interval.

the throughput as a function of L_{idl} with $\rho_{VO} : \rho_{VI} : \rho_{BE} = 15 : 10 : 1$ as the transmission opportunity of each AC, as shown in Fig. 4.1. Several important observations are made. First, I 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 high throughput. Therefore, L_{idl} is a suitable measure that indicates the network throughput.

In Fig. 4.1, 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 the equation (3.7), according to the number of nodes, each node can set the CW_{op} that $CW_{op} = 2nL_{idl} + 1$. Since I am interested in tuning the network to obtain maximal throughput, given the linear relationship, I 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.

4.3.2 Enhancement of QoS

I introduced a method to maximize total throughput under the condition that all nodes are in the saturation status and the same situation in Chapter 3. Here, I 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, I 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 [40]. 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, I 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

$$\begin{aligned} \eta_{VO} &= \frac{\rho_{VO}}{\rho_{VO} + \rho_{VI} + \rho_{BE}} \\ \eta_{VI} &= \frac{\rho_{VI}}{\rho_{VO} + \rho_{VI} + \rho_{BE}} \\ \eta_{BE} &= \frac{\rho_{BE}}{\rho_{VO} + \rho_{VI} + \rho_{BE}}. \end{aligned} \tag{4.4}$$

Also, the attempt probability can be expressed as $p = 2/(CW_{op} + 1)$ from equation (5.1). 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

$$\begin{aligned} CW[VO] &= \frac{1}{\eta_{VO}} \cdot (CW_{op} + 1) - 1 \\ CW[VI] &= \frac{1}{\eta_{VI}} \cdot (CW_{op} + 1) - 1 \\ CW[BE] &= \frac{1}{\eta_{BE}} \cdot (CW_{op} + 1) - 1. \end{aligned} \tag{4.5}$$

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. I prove it by simulation results in section 4.4. 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.

4.3.3 OBQ Scheme

With equation (3.4), for estimating the number of nodes, I 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

$$\begin{aligned} P_{idl} &= \frac{C_{idl}}{C_{idl} + C_s + C_{col}} \\ P_s &= \frac{C_s}{C_{idl} + C_s + C_{col}} \\ P_{col} &= \frac{C_{col}}{C_{idl} + C_s + C_{col}}. \end{aligned} \tag{4.6}$$

I can obtain the CW_{op} by equation (3.7) 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 equation (4.5) can be set freely. In following, I 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 transmission 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.

4.4 Performance evaluations

In this section, I evaluate the performance of our OBQ through simulations, which are carried out on OPNET Modeler [27]. For comparison purpose, I 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 4.1 and the OBQ-specific parameters in TABLE 4.2. 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, I 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

Table 4.1: 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
$CW_{min}[VO] \sim CW_{max}[VO]$	$7 \sim 15$
$CW_{min}[VI] \sim CW_{max}[VI]$	$15 \sim 31$
$CW_{min}[BE] \sim CW_{max}[BE]$	$31 \sim 1023$
Max retry threshold	7
Buffer size	256000 bits
Background noise	-101dBm
Data rate	11Mbps

Table 4.2: Backoff parameters

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

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.

4.4.1 Estimating number of nodes

OBQ can estimate the number of nodes dynamically in saturated case. Fig. 4.2 shows the estimated number of nodes of a node with condition of 50 nodes in offered load 1. From Fig. 4.2, I 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

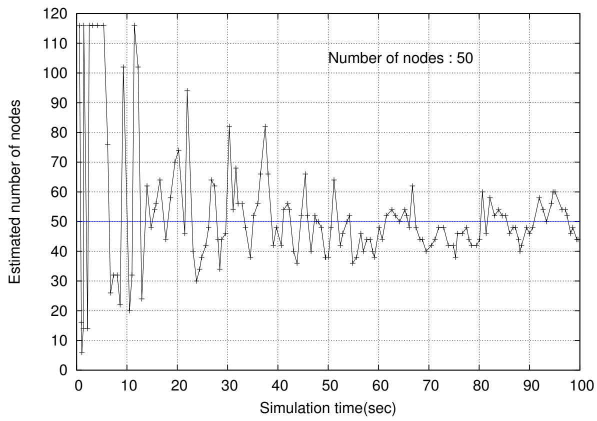


Figure 4.2: Estimated number of nodes vs. simulation time.

related to algorithm of backoff parameters shown in TABLE 4.2.

4.4.2 Throughput

First, since all nodes can obtain the almost same total throughput, I 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. Figs. 4.3, 4.4 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. 4.3, I 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. 4.4, the packet sizes are set as 1280 and

1500 bytes longer than above case. The same change tendency can be found like Fig. 4.3. 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. Fig. 4.5 shows the total throughputs when the CW ratio is changed. The CW ratio has a little effect on the total throughput performance.

Fig. 4.6 shows the maximum total throughputs with different packet sizes. Because the CW ratio has a little effect on the total throughput performance, Fig. 4.6 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 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 equation (4.1), maximum error about 4 %.

I evaluate the performance of our OBQ in an environment close to the real world. Fig. 4.7 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 affect 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. 4.8 shows the total throughput when the traffics vary. In Fig. 4.8, 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.

4.4.3 Delay

Figs. 4.9, 4.10 show the delay and the throughput results of 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. Fig. 4.9 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 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. I describe in detail in the next section of data dropped. Fig. 4.10 shows the delay and the throughput results of AC[BE]. The delay of OBQ

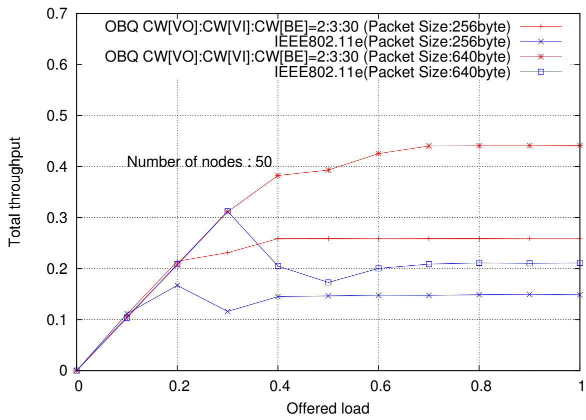


Figure 4.3: Total throughput of OBQ and IEEE 802.11e with different packet size.

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.

Figs. 4.11, 4.12 show the delay results of each AC when CW ratio is changed. Figs. 4.11 shows the delay results of AC[VO] and AC[VI]. The delay is changed according to CW ratio. Fig. 4.12 shows the delay result of AC[BE]. The same change tendency can be found like Fig. 4.11. Thus, the delay of each AC of OBQ changes but the changes of total throughput are not clearly when CW ratio is changed.

4.4.4 Data Dropped

Fig. 4.13 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 axis expresses the sum of buffer overflow and retry threshold exceeded and horizontal axis expresses normalized offered total traffic. As shown in Figs. 4.3, 4.4, 4.5, OBQ maintains high throughput even if CW ratio is changed. Therefore, the data dropped is minimal 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 4.4. 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

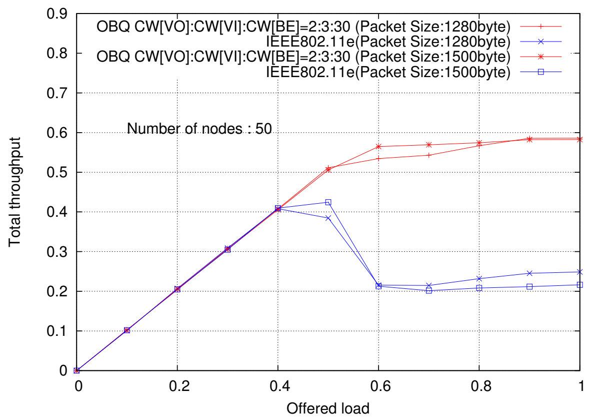


Figure 4.4: Total throughput of OBQ and IEEE 802.11e with different packet size.

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.

4.4.5 Fairness

To evaluate the fairness of OBQ, I adopt the following Fairness Index (FI) [29] that is commonly accepted:

$$FI = \frac{(\sum_{i=1} T_i/\phi_i)^2}{n\sum_{i=1}(T_i/\phi_i)^2} \tag{4.7}$$

where T_i is total throughput of flow i, ϕ_i is the weight of flow i (normalized total throughput requested by each node). Here, I assume all nodes have the same weight in simulation. According to equation (4.7), $FI \leq 1$, where the equation holds only when all T_i/ϕ_i are equal. Normally, a higher FI means a better fairness.

Fig. 4.14 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 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.

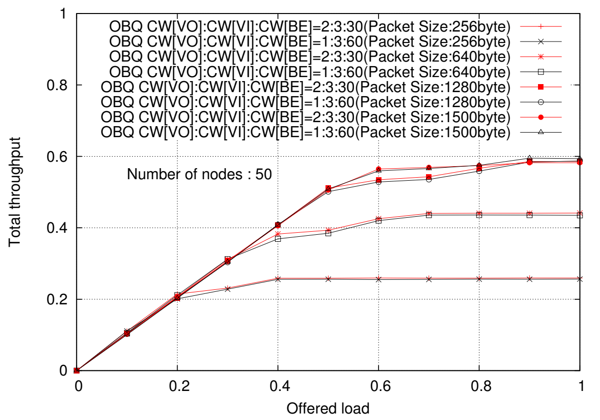


Figure 4.5: Total throughput vs. offered load when the CW ratio is changed.

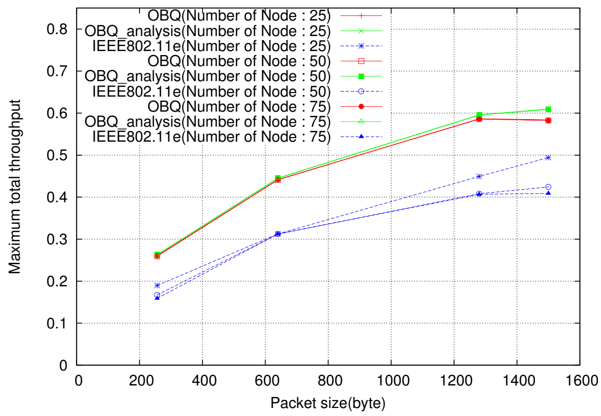


Figure 4.6: Maximum total throughput with different frame lengths.

4.4.6 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, I 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 $CW[VO] : CW[VI] : CW[BE] = 2 : 3 : 30$. Fig. 4.15 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

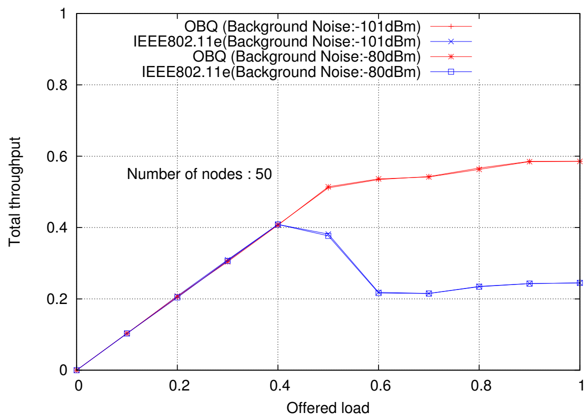


Figure 4.7: Total throughput vs. offered load when the background noise varies.

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 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.

Fig. 4.16 shows the delay results of AC[VO]. In Fig. 4.16, the delay of OBQ is lower than that of the IEEE 802.11e in non-saturated case but not in saturated case like Fig. 4.9. 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.

4.5 Conclusions

In this section, I 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 traffics situation of each node changes, total

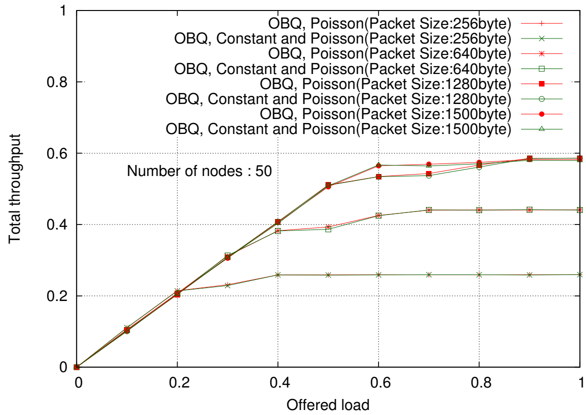


Figure 4.8: Total throughput vs. offered load when the traffics vary.

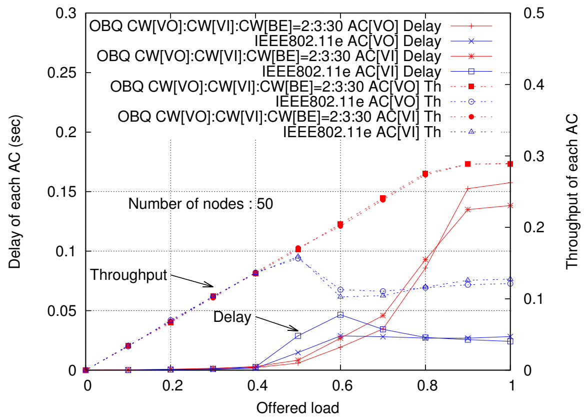


Figure 4.9: Delay and throughput of AC[VO] and AC[VI] vs. offered load.

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.

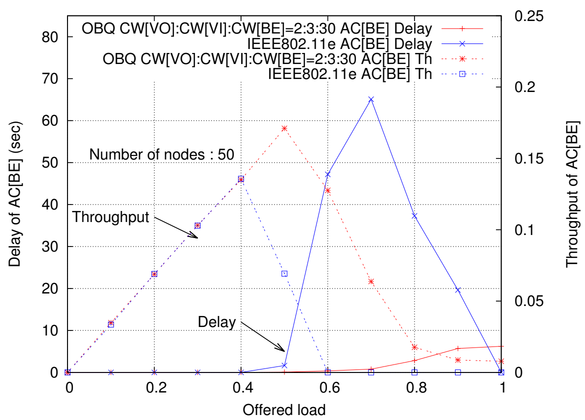


Figure 4.10: Delay and throughput of AC[BE] vs. offered load.

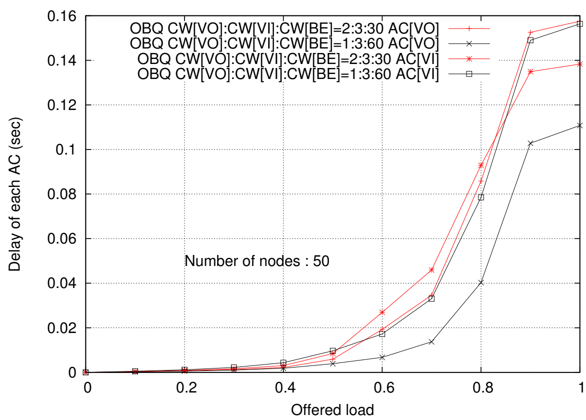


Figure 4.11: Delay of AC[VO] and AC[VI] vs. offered load when the CW ratio is changed.

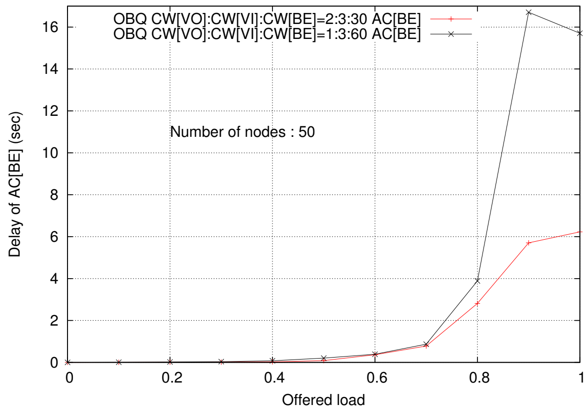


Figure 4.12: Delay of AC[BE] vs. offered traffic when the *CW* ratio is changed.

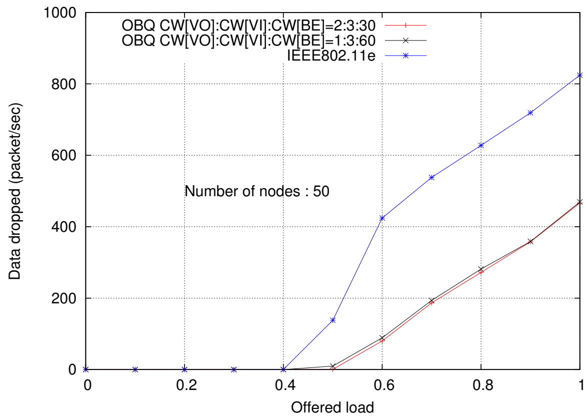


Figure 4.13: Data dropped vs. offered traffic when the *CW* ratio is changed.

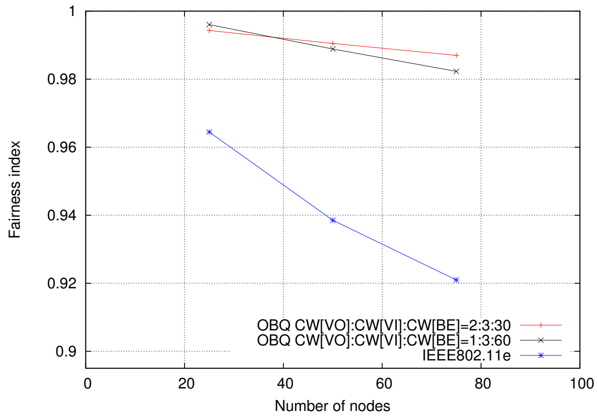


Figure 4.14: Fairness index when the CW ratio is changed.

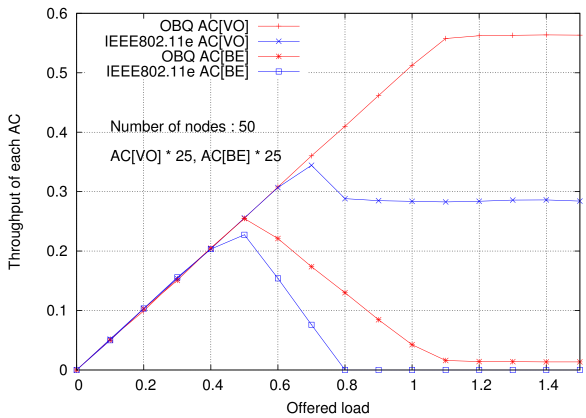


Figure 4.15: Throughput of each AC vs. offered load when the traffic configuration is changed.

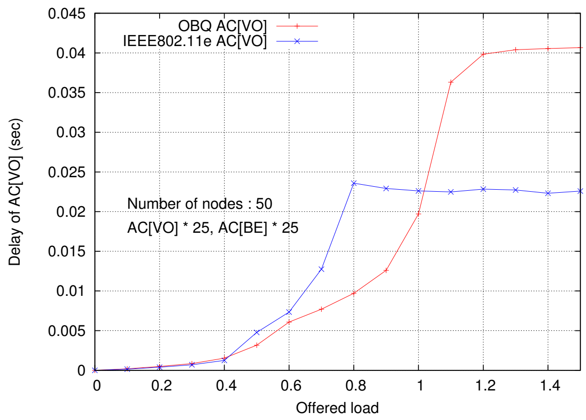


Figure 4.16: Delay of AC[VO] vs. offered load when the traffic configuration is changed.

Chapter 5

5. Improving the throughput and the fairness in multi-hop

The Chapter 3 and 4 proposed the novel MAC protocol OBEN, OBQ, respectively. They assume that the network is in single-hop wireless network. In actual network, the multi-hop wireless network is used as well as single-hop wireless network. Although the multi-hop wireless network can be adjusted in wide network, the severe problems occur. For this reason, the throughput decreases sharply. Thus, I propose the novel MAC protocol that Optimizing Backoff by dynamically Estimating the number of nodes in Multi-hop networks. I call it OBEM. OBEM can alleviate the sever problems and improve the throughput in multi-hop wireless network.

The remainder of this chapter is organized as follows. The Section 5.1 explains the problems of the conventional method. In Section 5.2, I introduce the related work in term of the multi-hop wireless network. In Section 5.3, I elaborate on our key idea and the theoretical analysis for improvement. Then, I present in detail our proposed OBEM scheme. The Section 5.4 gives performance evaluation and the discussions on the simulation results. Finally, concluding remarks are given in Section 5.5.

5.1 Problems of the conventional method

OBEN and OBQ assume that all nodes communicate each other, that is single-hop wireless network. On the other hand, in multi-hop wireless network, the transmission range of a node is not large enough to transmit to every nodes in the entire network area. In that case, the transmission between two nodes may require more than one hop. Thus, the throughput decreases rapidly due to the hidden node problem. To alleviate the hidden node problem, RTS/CTS mechanism is widely accepted. The transmission node transmits the RTS packet and the receiver node transmits the CTS packet. By that communication, the channel is reserved and the transmission node can transmit the data packet safety. However, the exposed node problem and the receiver blocking problem occur prominently. Thus, these problems need to be alleviated

5.2 Related works

Several researches have been proposed in [41, 42, 43, 44, 45, 46, 47, 48] for alleviating the hidden node problem. In [41, 42, 43, 44, 45], the multi-channel MAC protocol was proposed. In [42], the authors proposed a MAC protocol, which employs two radio interfaces per node. One interface follows fast hopping and is mainly for transmission, while the other interface follows slow hopping and is generally for reception. The works in [44, 45] adopt the busy tone to deliver the data packets successfully. The other nodes that hear the busy tone should suspend their attempts for data transmissions. In [47], the authors proposed the multiple receiver transmission (MRT), the fast NAV (Network Allocation Vector) truncation (FNT) and the adaptive receiver transmission (ART) scheme. For alleviating the receiver blocking problem, each node transmits to multiple receivers in MRT scheme and the NAV duration in RTS packet reduces in FNT protocol. Considering the drawbacks from the MRT and FNT schemes, the ART scheme further improves the throughput.

The above most works are used in limited network and not flexible enough. For example, the works in [44, 45] assume that each network node needs to use at least two transceivers, which is merely utilized in wireless networks. The MRT and ART schemes in [47] assume that each node has multiple destination nodes. Also, most works do not take the backoff process into account to improve the throughput. In multi-hop wireless networks, the collisions are caused by the neighbor nodes or the hidden nodes, which is more than single-hop wireless networks. Thus, for improving the throughput, the optimal backoff process is required to avoid the collisions. In this chapter, for expanding OBEN in multi-hop wireless networks, I propose a novel MAC protocol that dynamically optimizes each node's backoff process for multi-hop wireless networks. The models on throughput analysis have been investigated in [49, 50, 51, 52] for multi-hop wireless networks. These models is referred in the performance analysis of proposed OBEM.

5.3 Analysis and the proposal of optimizing backoff by dynamically estimating number of nodes

5.3.1 Optimal backoff

In the IEEE 802.11 MAC, an appropriate CW (Contention Window) is the key to providing throughput and fairness. In [13], the DCF is analyzed based on the 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 OBEM would enable all the nodes to settle on a quasi-table CW shortly after the network is put into operation, for simplicity I assume that all the nodes use the same and fixed CW. Consequently, I have

$$p = \frac{2}{CW + 1} \tag{5.1}$$

as all the expectation sings E can be removed. In multi-hop wireless networks, the collisions are caused by the neighbor nodes or the hidden nodes, which is more than single hop. Thus, network nodes need to obtain the optimal CW in order to avoid the collisions. In OBEM, by observing the channel, all nodes adjust the optimal CW and obtain high throughput.

5.3.2 Analysis of Throughput in Multi-hop Networks

The analytical model is classified into a tagged node, the neighbor nodes and the hidden nodes, as shown in Fig.5.1. For simplicity, the transmission, interference and sensing rages for all network nodes are the same value. The neighbor node is in a tagged node's transmission range. The hidden node is outside the transmission range of the tagged node and within the transmission range of the transmission destination of the tagged node. The range of the hidden node is indicated by the horizontal line in Fig.5.1. I can divide the state of each node (a tagged node, neighbor node and hidden node) into idle, one transmission or transmissions. By calculating the probabilities of each state, the throughput of the tagged node can be obtained. In the following, I give the probabilities of each state.

The tagged node and neighbor nodes are idle

The tagged node in the idle state means that the tagged node does not transmit RTS packet, the probability that the tagged node is in the idle state is denoted by $P_{t0} = 1 - p$. And the neighbor nodes are in the idle state, the probability of the state is denoted by $P_{t0\_n0} = (1 - p)^{1+n}$, where n is the number of neighbor nodes. And, the hidden nodes are in the idle state, the probability of the state is denoted by $P_{t0\_n0\_h0}$, it can be expressed as

$$P_{t0\_n0\_h0} = (1 - p)^{1+n+h(r)} \tag{5.2}$$

,where $h(r)$ is the number of hidden nodes and depends on r. h(r) is calculated as $h(r) = \left(\pi R_{tx}^2 - 2R_{tx}^2 \left(acos(\frac{r}{2R_{tx}}) - \frac{r}{2R_{tx}}\sqrt{1 - (\frac{r}{2R_{tx}})^2}\right)\right)\theta$, where r, R_{tx} and θ are the distance between the transmitter and the receiver, the radius of the transmission range and the density of nodes, respectively. In this

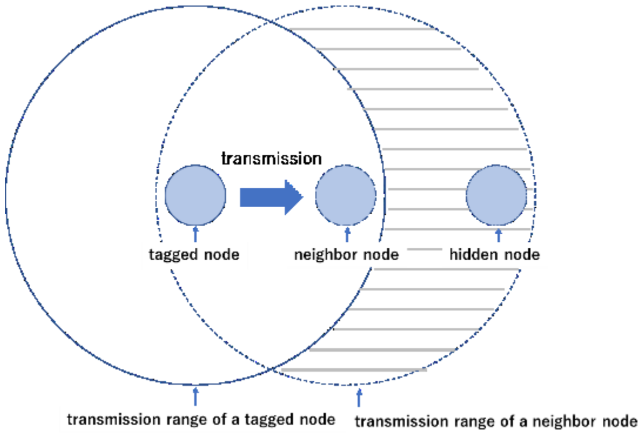


Figure 5.1: Classification of each node

state, all nodes (tagged node, neighbor nodes, hidden nodes) do not transmit any packets. The duration of the state is denoted by $T_{t0\_n0\_h0} = slot_t ime$. When only one hidden node transmits the RTS packet, the probability of the state is denoted by $P_{t0\_n0\_h1}$, it can be can expressed as

$$P_{t0\_n0\_h1} = h(r)p\,(1-p)^{1+n+(h(r)-1)\eta_{RTS}} \tag{5.3}$$

where η_{RTS} is the duration that the node does not transmits the RTS packet, which can be calculated as $\eta_{RTS} = \frac{T_{RTS}+SIFS}{slot_t ime}$. T_{RTS} is the transmission duration for a RTS packet. In fact, the hidden node is successful transmission when the neighbor and hidden nodes of the hidden node need to be idle, which is complex. For simplicity, I assume that the transmission of this state is successful. The duration of the state is denoted by $T_{t0\_n0\_h1} = T_{RTS} + T_{CTS} + T_{data} + T_{ACK} + 3SIFS + DIFS + 4\tau$, where T_{CTS}, T_{data}, T_{ACK} are the transmission duration for a CTS packet. τ is the maximum propagation delay between two nodes. When two or more hidden nodes transmit RTS packet simultaneously, the probability of the state is denoted by $P_{t0\_n0\_h2}$. With the complementary event, it can be expressed as

$$P_{t0\_n0\_h2} = P_{t0\_n0} - (P_{t0\_n0\_h0} + P_{t0\_n0\_h1})\,. \tag{5.4}$$

This state means the collision. The duration of the state is denoted by $T_{t0_n0_h1} = T_{RTS} + EIFS + \tau$.

The tagged node is idle and only one neighbor node is transmission

The probability of the state that the tagged node is idle state and only one neighbor node is one transmission state is denoted by $P_{t0\_n1} = np\,(1-p)^n$.

And then, when the hidden nodes are idle, the probability of the state is denoted by $P_{t0\_n1\_h0}$, it can be expressed as

$$P_{t0\_n1\_h0} = np\,(1-p)^{n+h(r)}\,. \qquad (5.5)$$

The state is successful transmission for a neighbor node, the duration of the state is denoted by $T_{t0\_n0\_h0} = T_{RTS} + T_{CTS} + T_{data} + T_{ACK} + 3SIFS + DIFS + 4\tau$. On the other hand, when one or more hidden nodes transmit the RTS packet, the probability of the state is denoted by $P_{t0\_n1\_h1}$, it can be expressed as

$$P_{t0\_n1\_h1} = P_{t0\_n1} - P_{t0\_n1\_h0}. \qquad (5.6)$$

This state is collision and the duration of the state is denoted by $T_{t0\_n0\_h1} = T_{RTS} + EIFS + \tau$.

The tagged node is idle and two or more neighbor nodes are transmission

The probability of the state that the tagged node is idle state and two or more neighbor nodes are transmission state is denoted by P_{t0_n2}. With the complementary event, the probability is expressed as

$$P_{t0\_n2} = P_{t0} - (P_{t0\_n0} + P_{t0\_n1}) \qquad (5.7)$$

This state is collision and the duration of $T_{t0_n2} = T_{RTS} + EIFS + \tau$.

The tagged node is transmission and neighbor nodes are idle

The tagged node is transmission state and the probability of the state is denoted by $P_{t1} = p$. Similarly, the neighbor nodes are idle state, the probability of the state is denoted by $P_{t1\_n0} = p\,(1-p)^n$. Moreover, when the hidden node is idle, the probability of the state is denoted by $P_{t1\_n0\_h0}$, it can be expressed as

$$P_{t1\_n0\_h0} = p\,(1-p)^{n+h(r)\eta_{RTS}} \qquad (5.8)$$

This state is successful transmission for the tagged node, the duration of the state is denoted by $T_{t1\_n0\_h0} = T_{RTS} + T_{CTS} + T_{data} + T_{ACK} + 3SIFS + DIFS + 4\tau$. On the other hand, when one or more hidden nodes transmit the RxTS packet, the probability of the state is denoted by $P_{t1\_n0\_h1}$, it can be expressed as

$$P_{t1\_n0\_h1} = P_{t1\_n0} - P_{t1\_n0\_h0} \qquad (5.9)$$

This state is collision. The duration of the state is denoted by $T_{t1\_n0\_h1} = T_{RTS} + EIFS + \tau$.

Table 5.1: The probabilities of each node state

Tagged node	Probability	Neighbor node	Probability	Hidden node	Probability	Period [slots]
Idle	$P_{t0} = 1-p$	Idle	$P_{t0\_n0} = (1-p)^{1+n}$	Idle	$P_{t0\_n0\_h0} = (1-p)^{1+n+H(r)}$	$T_{t0\_n0\_h0} = slot\_time$
				One transmission	$P_{t0\_n0\_h1} = pH(r)(1-p)^{1+n+(H(r)-1)\eta_{RTS}}$	$T_{t0\_n0\_h1}$=T_RTS+T_CTS+T_data+T_ACK+4*tau+3*SIFS+DIFS
				Transmission of 2 or more nodes	$P_{t0\_n0\_h2} = P_{t0\_n0} - (P_{t0\_n0\_h0} + P_{t0\_n0\_h1})$	$T_{t0\_n0\_h2}$=T_RTS + tau + EIFS
		One transmission	$P_{t0\_n1} = np(1-p)^n$	Idle	$P_{t0\_n1\_h0} = np(1-p)^{n+H(r)}$	$T_{t0\_n1\_h0}$=T_RTS+T_CTS+T_data+T_ACK+4*tau+3*SIFS+DIFS
				Transmission of 1 or more nodes	$P_{t0\_n1\_h1} = P_{t0\_n1} - P_{t0\_n1\_h0}$	$T_{t0\_n1\_h1}$=T_RTS + tau + EIFS
		Transmission of 2 or more nodes	$P_{t0\_n2} = P_{t0} - (P_{t0\_n0} + P_{t0\_n1})$	-	-	T_{t0_n2}=T_RTS + tau + EIFS
transmission	$P_{t1} = p$	Idle	$P_{t1\_n0} = p(1-p)^n$	Idle	$P_{t1\_n0\_h0} = p(1-p)^{n+H(r)\eta_{RTS}}$	$T_{t1\_n0\_h0}$ = T_RTS+T_CTS+T_data+T_ACK+4*tau+3*SIFS+DIFS
				Transmission of 1 or more nodes	$P_{t1\_n0\_h1} = P_{t1\_n0} - P_{t1\_n0\_h1}$	$T_{t1\_n0\_h1}$=T_RTS + tau + EIFS
		Transmission of 1 or more nodes	$P_{t1\_n1} = P_{t1} - P_{t1\_n0}$	-	-	T_{t1_n1}=T_RTS + tau + EIFS

The tagged node is transmission and one or more neighbor nodes are transmission

When the tagged node is transmission state and one or more neighbor nodes are also transmission state, the probability of the state is denoted by P_{t1_n1}. With the complementary event, it can be expressed as

$$P_{t1\_n1} = P_{t1} - P_{t1\_n0}. \tag{5.10}$$

This state is also collision. The duration of the state is denoted by $T_{t1_n0_h1} = T_{RTS} + EIFS + \tau$. As above, I classified the state according to each node in multi-hop networks and calculated the probability of the state, as shown in Table 5.1.

5.3.3 Optimal Backoff

Using the above probabilities of each state, the throughput per a node is expressed as

$$\rho = \frac{data\ P_{t1\_n0\_h0}}{\left(\sum_{i=0}^{2} P_{t0\_n0\_hi}T_{t0\_n0\_hi}\right) + \left(\sum_{i=0}^{1} P_{t0\_n1\_hi}T_{t0\_n1\_hi}\right) + P_{t0\_n2}T_{t0\_n2} + \left(\sum_{i=0}^{1} P_{t1\_n0\_hi}T_{t1\_n0\_hi}\right) + P_{t1\_n1}T_{t1\_n1}} \tag{5.11}$$

The data is the total number of bits in the payload. Our aim is to maximize the throughput shown in Equation. (5.11). To this end, I need to obtain the optimal CW according to the network condition such as the number of the neighbor nodes and the hidden nodes. In the following, I give the method for estimating the number of the neighbor nodes and the hidden nodes on line by four parameters $P_{t0\_n0\_h0}$, $P_{t0\_n0\_h1}$, $P_{t0\_n1\_h0}$ and $P_{t1\_n0\_h0}$, which can be obtained directly by listening to the channel for a certain interval. Then, using obtained $P_{t0\_n0\_h0}$, $P_{t0\_n0\_h1}$, $P_{t0\_n1\_h0}$ and $P_{t1\_n0\_h0}$, I give the method for maximizing the throughput dynamically. I use a simple and effective method which is suitable for real time estimating. From Equation. (5.2) and (5.5), I have $p = \frac{P_{t0\_n1\_h0}}{nP_{t0\_n0\_h0}+P_{t0\_n1\_h0}}$. From Equation. (5.3) and (5.8), I have $p = 1 - \left(\frac{h(r)P_{t1\_n0\_h0}}{P_{t0\_n0\_h1}}\right)^{\frac{1}{21}}$, where η_{RTS} is constant value and equals to 22 in IEEE 802.11b. With the above equations and Equation. (5.2), I can obtain

$$P_{t0\_n0\_h0} = \left(1 - \frac{P_{t0\_n1\_h0}}{nP_{t0\_n0\_h0} + P_{t0\_n1\_h0}}\right)^{1+n+h(r)} \tag{5.12}$$

$$h\left(r\right) = \left(1 - \frac{P_{t0\_n1\_h0}}{nP_{t0\_n0\_h0} + P_{t0\_n1\_h0}}\right)^{21} \frac{P_{t0\_n0\_h1}}{P_{t1\_n0\_h0}}. \tag{5.13}$$

Let $f_{idl}(n) = \left(1 - \frac{P_{t0\_n1\_h0}}{nP_{t0\_n0\_h0}+P_{t0\_n1\_h0}}\right)^{1+n+h(r)}$, where $P_{t0\_n0\_h0}$ and $P_{t0\_n1\_h0}$ are known parameters and, n and $h(r)$ are unknown parameters that needs to be estimated. I can estimate the number of the neighbor nodes and the hidden nodes by the simple calculation method, without solving a complicated equation. As show in Fig. 5.2, the function $f_{idl}(n)$ increases as the number of neighbor nodes is increasing. Since $P_{t0\_n0\_h0}$ is a known value, $f_{idl}(n)$ should be adjusted in agreement with $P_{t0\_n0\_h0}$. When $P_{t0\_n0\_h0}$ is equal to $f_{idl}(n)$, n is the number of neighbor nodes deployed in real network. The above characteristic is favorable for estimating the number of neighbor nodes n and the hidden nodes $h(r)$ 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 $h\left(r\right)$ is computed with n_{try1} as shown in Equation. (5.12). Substitute n_{try1} and $h\left(r\right)$ into $f_{idl}(n)$, and compare $f_{idl}\left(n_{try1}\right)$ with $P_{t0\_n0\_h0}$. If $f_{idl}\left(n_{try1}\right) > P_{t0\_n0\_h0}$, I should set $n_{try2} = (n_{try1} + n_{max})/2$. Otherwise, I should set $n_{try2} = (n_{try1} + 0)/2$ for the following calculation. Obviously, this method is simple and effective. For example, when $n_{max} = 200$, I just need to calculate four times to estimate n in the worst case with maximum error 6. In the following, I present the condition of high throughput. And then, I give the method of how to dynamically tune CW to enhance throughput and fairness. The average idle slot interval is denoted by L_{idl}, it can be expressed as

$$L_{idl} = \frac{P_{t0\_n0\_h0}}{1 - P_{t0\_n0\_h0}} \tag{5.14}$$

With Equations. (5.1), (5.2) and (5.14), this equation can be further written

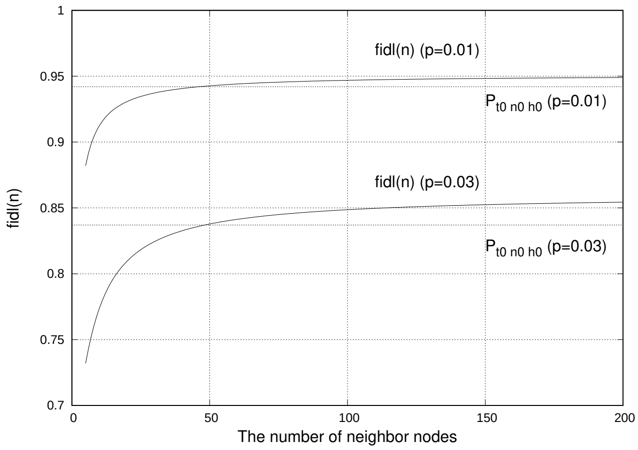


Figure 5.2: The $f_{idl}(n)$ when the real value of n is 50

as

$$\begin{aligned} L_{idl} &= \frac{1}{\left(1+\frac{2}{CW-1}\right)^{n\prime}-1} \\ &= \frac{1}{(n\prime\frac{2}{CW-1}+\ldots+\begin{pmatrix} n\prime \\ i \end{pmatrix}(\frac{2}{CW-i})^{n\prime-i}+\ldots+(\frac{2}{CW-1})^{n\prime}} \end{aligned} \quad (5.15)$$

where $n' = 1 + n + h\,(r)$. I can simplify Equation. (5.15) as

$$L_{idl} = \frac{CW-1}{2n\prime} \quad (5.16)$$

I can obtain Equation. (5.16) 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 is large enough for the approximation $L_{idl} = (CW-1)/(2(1+n+h\,(r))$ in our OBEM.

With Equations. (5.11) and (5.16), thinking IEEE 802.11b, we can express the throughput per a node as a function of L_{idl}, as shown in Fig. 5.3 and 5.4. From the figures, first, we find that every curve follows the same pattern; namely, as the average idle slot interval L_{idl} increases, the throughput first rises quickly, and then decreases relatively slowly after reaching its peak. Second, although the optimal value of L_{idl} that maximizes throughput is different in cases of different ratio of the number of neighbor nodes to the number of hidden nodes. The range of the optimal L_{idl} is $[4, 28]$ when $n \geq h(r)$. Finally, this optimal value is almost independent of the ratio of the number of hidden nodes to the number of neighbor nodes. As shown in Fig. 5.4, when the ratio is 0.1, the optimal L_{idl} is 13. When the ratio

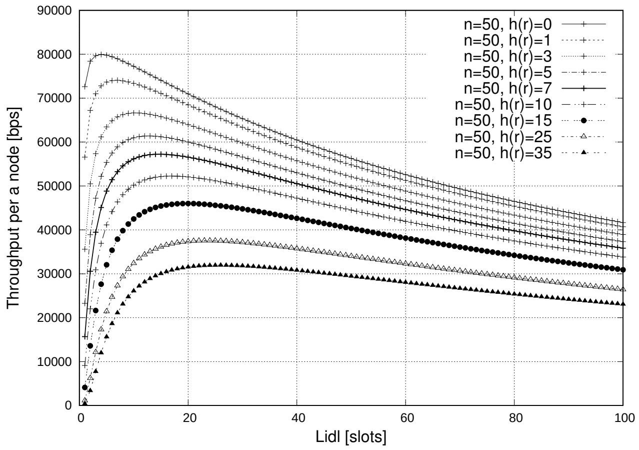


Figure 5.3: Throughput with average idle interval when the ratio of n to $h(r)$ is changed

is 0.5, the optimal L_{idl} is 23. The optimal L_{idl} is not changed when the number of neighbor nodes or the number of hidden nodes unless the ratio is not changed. Therefore, if nodes can estimate the number of neighbor nodes and the number of hidden nodes correctly, they can set the optimal CW by using the optimal L_{idl} and the estimated nodes to achieve high throughput. From the above Equation. (5.11), according to the number of neighbor nodes and the hidden nodes, each node can set the optimal CW that $CW = 2\,(1 + n + h\,(r))\,L_{idl} + 1$. Since we are interested in tuning the network to obtain maximal throughput, we can achieve this goal by adjusting the size of CW. In other words, each node can estimate the number of neighbor nodes and hidden nodes and adjust its backoff window accordingly so that the throughput of the network is maximized.

5.3.4 OBEM Scheme

As mentioned above, OBEM can obtain the optimal CW by Equation. (5.16) by using the estimated number of active nodes. Hence, each node can adjust its CW dynamically and tune the network to deliver high throughput. To obtain the $P_{t0_n0_h0}$, $P_{t0_n0_h1}$, $P_{t0_n1_h0}$ and $P_{t1_n0_h0}$, each node can count the number of idle slots (C_{idl}), received RTS packets (C_{RTS}), received CTS packets (C_{CTS}), successful transmissions of tagged node (C_s) and collisions (C_{col}) individually. To avoid occasional cases, C_{idl}, C_{RTS}, C_{CTS}, C_s and C_{col} are expected to be measured in resetting the counters before a transmission. The $P_{t0\_n0\_h0}$, $P_{t0\_n0\_h1}$, $P_{t0\_n1\_h0}$ and $P_{t1\_n0\_h0}$ can be calculated as

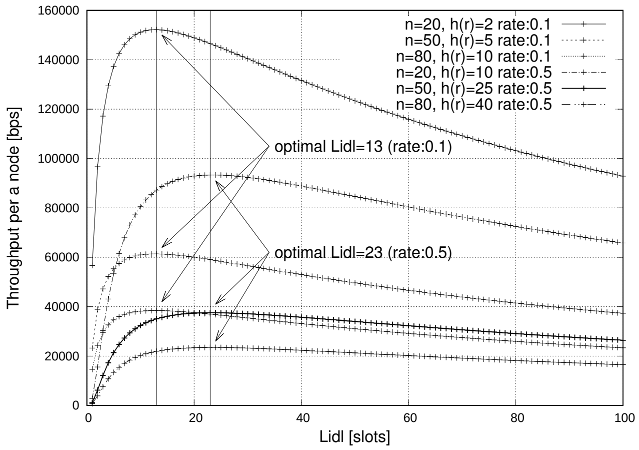


Figure 5.4: Throughput with average idle interval when the ratio of n to $h(r)$ are 0.1 and 0.5

$$
\begin{aligned}
P_{t0\_n0\_h0} &= \frac{C_{idl}}{C_{idl} + C_{RTS} + C_{CTS} + C_s + C_{col}} \\
P_{t0\_n0\_h1} &= \frac{C_{CTS} - C_{RTS}}{C_{idl} + C_{RTS} + C_{CTS} + C_s + C_{col}} \\
P_{t0\_n0\_h0} &= \frac{C_{RTS}}{C_{idl} + C_{RTS} + C_{CTS} + C_s + C_{col}} \\
P_{t0\_n0\_h0} &= \frac{C_{col}}{C_{idl} + C_{RTS} + C_{CTS} + C_s + C_{col}} \qquad (5.17)
\end{aligned}
$$

Since different MAC protocols have different definitions of time interval such as DIFS, SIFS, slot time may need to be adjusted. Using the above events, each node estimates the number of neighbor nodes and hidden node. In multi-hop wireless networks, the channel events listened by each node may be different, which induce the degraded fairness. Since the fairness also improve, RTS packet adds the estimated number of neighbor nodes and hidden nodes. Moreover, a node estimates the number of neighbor nodes n and hidden nodes $h(r)$. After new n and $h(r)$ is obtained, theses can be updated as

$$
\begin{aligned}
n &= \alpha n_{ave} + (1 - \alpha)\, n \\
h(r) &= \beta h(r)_{ave} + (1 - \beta)\, h(r) \qquad (5.18)
\end{aligned}
$$

where n_{ave} and $h(r)_{ave}$ are the average value of n and $h(r)$, which are computed by receiving the RTS packets with n and $h(r)$. Also, α and β are the smoothing factor with the range of $[0, 1]$. The higher α and β leads to stability but maybe reduces adaptivity to network changes such as traffic and active nodes. In OBEM, the sizes of n and $h(r)$ are largely varied by little changes in the probabilities of each state, which results in degraded throughput and fairness. For minimizing the variation of CW and adjusting the changes in the number of nodes, I set $\alpha = \beta = 0.8$ in simulation results in the next section. The ratio of the number of hidden nodes to the number of neighbor nodes is denoted by σ. From the Fig. 5.3, each node computes the optimal L_{idl} as follows.

$$\begin{aligned}
IF\,(\sigma \leq 0.0125)\,L_idl &= 4 \\
IF\;\;(0.0125 < \sigma\;\; \leq 0.0375)\;\;L_{idl} &= 7 \\
IF\;\;(0.0375 < \sigma\;\; \leq 0.075)\;\;L_{idl} &= 10 \\
IF\;\;(0.075 < \sigma\;\; \leq 0.125)\;\;L_{idl} &= 13 \\
IF\;\;(0.125 < \sigma\;\; \leq 0.175)\;\;L_{idl} &= 15 \\
IF\;\;(0.175 < \sigma\;\; \leq 0.25)\;\;L_{idl} &= 17 \\
IF\;\;(0.25 < \sigma\;\; \leq 0.375)\;\;L_{idl} &= 20 \\
IF\;\;(0.375 < \sigma\;\; \leq 0.575)\;\;L_{idl} &= 23 \\
IF\,(0.575 < \sigma\;)\,L_{idl} &= 26
\end{aligned} \tag{5.19}$$

In the following, I give the tuning algorithm.

1. A node, say Node A, begins listening to a channel and counts events C_{idl}, C_{RTS}, C_{CTS}, C_s and C_{col}, individually.
2. When Node A needs backoff and the number of packet transmissions reaches a certain number γ, it calculates the optimal L_{idl} and CW.
3. It resets counting events of C_{idl}, C_{RTS}, C_{CTS}, C_s and C_{col}.

The certain number of packet transmissions needs to be set appropriately. When the number is small, CW changes rapidly with network changes. In contrast, if the number is large, the network can have higher stability but is short of adaptivity. In the following simulation, I set a certain number γ as 6. Ideally, each node should have the same CW when the network enters into a steady state in saturated case; in reality, each node sets its CW around the optimal value. Using this method, high throughput and good fairness are achieved, which can be found in the following simulations.

5.4 Performance evaluations

In this section, I focus on evaluating the performance of our OBEM through simulations, which are carried out on Riverbed. For comparison purpose, I also present the simulation results for the IEEE 802.11b DCF. The related parameters of IEEE 802.11b are shown in Table 5.2 and the OBEM-specific parameters in Table 5.3. In the conventional method, sets the maximum CW but in OBEM, there is no upper bound of CW. I assume that network nodes are deployed in circular as shown in Fig. 5.5. The Fig. 5.5 shows the network configuration that the number of neighbor nodes is 8 and the number of hidden nodes is 4. The number of nodes inside the transmission range is 8, which is the number of neighbor nodes. The number of nodes outside the transmission range of node 1 and inside the transmission range of node 5 is 4, which is the number of hidden nodes. Without a specific application, I assume that each node selects the fixed node as a receiver and generates traffic according to a Poisson process with the same arrival rate. The arrival rates are high enough to achieve the saturated network. For simplicity, each node does not use the ad-hoc routing protocol. As shown below, OBEM exhibits a better performance.

Table 5.2: Network configuration

Parameter	Value
Slot time	20μ sec
SIFS	10μ sec
DIFS	50μ sec
EIFS	364μ sec
Min CW - Max CW	31-1023
Max retry threshold	7
Buffer size	256000bits
Data rate	11Mbps
Network nodes	30
$(n, h(r))$	(24,5), (20,6),(10,4)

Table 5.3: Backoff parameters

Parameter	Value
n_{max}	200
α	0.8
β	0.8
γ	6

5.4.1 Estimated number of neighbor nodes and hidden nodes

Firstly, I give the estimated number of neighbor nodes and hidden nodes in OBEM. Fig. 5.6 shows the results of the estimated number of neighbor nodes and hidden nodes with simulation time when the number of neighbor nodes is 24 and the number of hidden nodes is 5. From Fig. 5.6, I find that the estimated number of neighbor nodes changes to inappropriate value

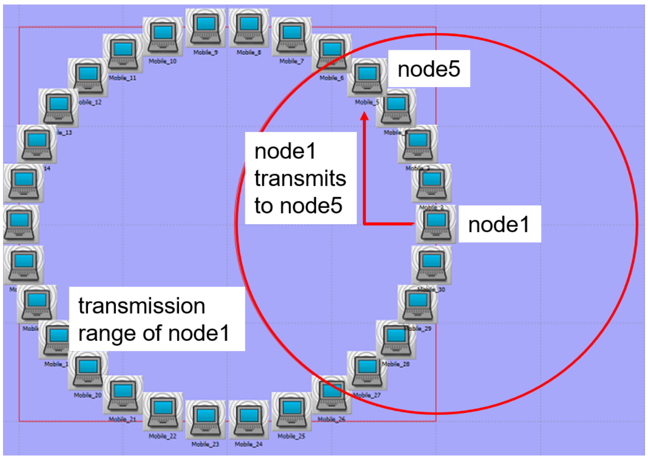


Figure 5.5: A snapshot of nodes distribution in simulation

because of the beginning of simulation and then converges to a comparatively stable value around 24 around 10s, which is related to algorithm of backoff parameters as shown in Table 5.3. Also, the estimated number of hidden nodes is around 5. Thus, OBEM can estimate the number of neighbor nodes and hidden nodes around real value.

5.4.2 Throughput

Second, I give the throughputs of OBEM and DCF. Fig. 5.7 shows the results of total throughput with different ratio of n to $h(r)$. The throughput is the only value of payload data successfully received and does not include other packets. When the ratio of n to $h(r)$ increases, the throughput increases because the number of nodes that can transmit at the same time increases. In DCF, there are many collisions by a binary exponential backoff algorithm. Because the nodes in DCF can not always have the optimal CW in saturated network, the throughput decreases. By contrast, the node in OBEM can obtain the CW around optimal CW according to the number of neighbor nodes and hidden nodes. The throughput of OBEM always is higher than DCF. Fig. 5.8 shows the results of total throughput with a different payload size when the number of neighbor nodes is 24 and the number of hidden nodes is 5. As the payload size increases, the payload transmission duration becomes longer, and the effect of the hidden node problem larger. Compared to DCF, OBEM can alleviate the hidden node problem. The throughput of OBEM always is higher than DCF. The maximum improvement of throughput is about 1.5 times when payload size is 12000.

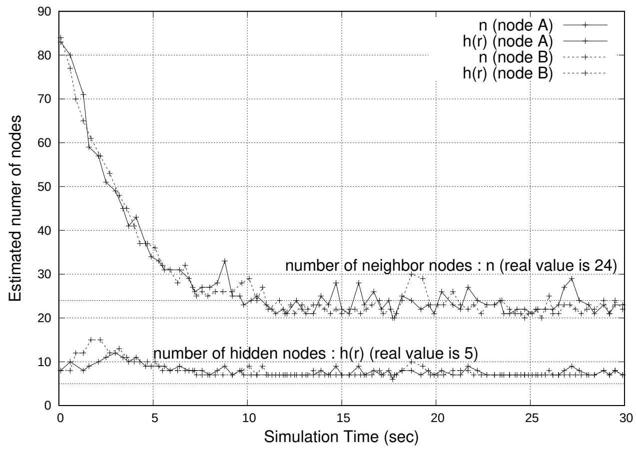


Figure 5.6: Estimated number of neighbor nodes and hidden nodes with simulation time

5.4.3 Fairness index

To evaluate the fairness of OBEM, I adopt the following Fairness Index (FI) [29] that is commonly accepted:

$$FI = \frac{(\sum_{i=1} T_i/\phi_i)^2}{n\sum_{i=1}(T_i/\phi_i)^2} \tag{5.20}$$

where $_i$ is the throughput of flow i, φ_i is the weight of flow i (normalized throughput requested by each node). Here, I assume all nodes have the same weight in simulation. According to Equation (5.20), FI≤1, where the equation holds only when all T_i/φ_i are equal. Normally, a higher FI means a better fairness. Fig. 5.9 shows the results with a different ratio of n to $h(r)$. From the figure, I can see that our proposal OBEM has the best fairness. The fairness of OBEM has no obvious changes. On the other hand, DCF degrades fairness heavily because the difference in the CW of each node is large by using a binary exponential backoff algorithm

5.5 Conclusions

This chapter proposed a novel MAC protocol OBEM that enhance DCF in multi-hop wireless networks. In OBEM, each node abserves C_{idl}, C_{RTS}, C_{CTS}, C_s and C_{col} to estimate the number of neighbor nodes and hidden nodes, and then sets CW around the optimal value dynamically. Thus, OBEM can obtain high throughput and good fairness. From analysis and simulation results, this scheme is effective and can adjust the network change promptly. Moreover, OBEM can alleviate the hidden node problem and

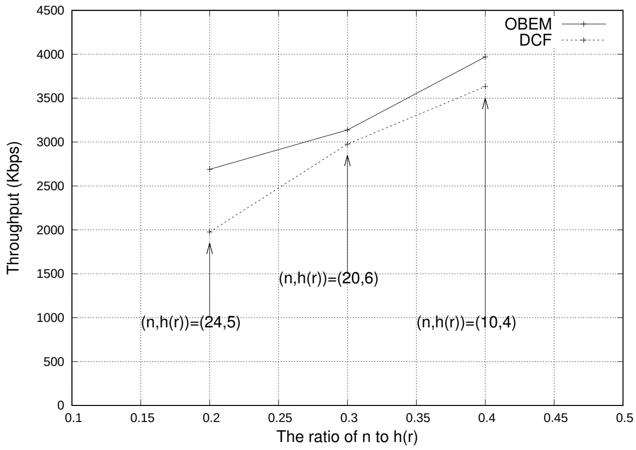


Figure 5.7: Throughput with a different ratio of n to h(r)

achieve higher throughput than IEEE 802.11 DCF. As a future work, I need verify by actual environment and evaluate the validity of OBEM.

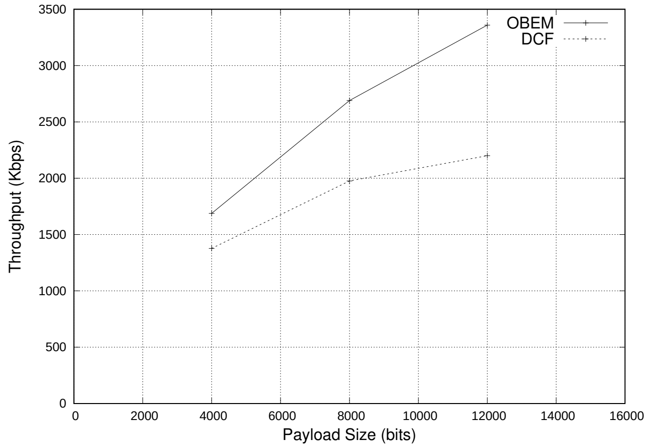


Figure 5.8: Throughput with a different payload size

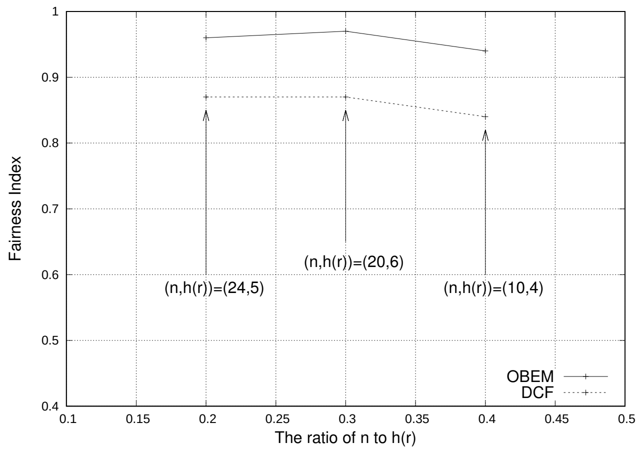


Figure 5.9: Fairness index

Chapter 6

Conclusions

6.1 Conclusions

The focus of this thesis is on DCF and EDCA for vehicle to vehicle communications. In vehicle to vehicle communications, each node can reach or leave the network freely. When much nodes enter a network, the throughput and fairness decreases sharply. To deploy a flexible and efficient network, the above problems need to be resolved. Thus, this thesis proposed the MAC protocols to resolve the above problems through 3 steps.

First, OBEN is proposed to improve the throughput and the fairness in single-hop network with DCF. In DCF, there is problem. When the number of nodes increases, the throughput decreases and the variation of the CW is large. The DCF applies an exponentiation backoff algorithm which can disperse retransmission timing among collision nodes. However, some nodes may defer time too long so that they cannot transmit for a long interval, which results in a poor fairness and throughput. OBEN resolved the problems of the conventional method DCF. In OBEN, each node just need to confirm if the channel is busy or idle to obtain the number of idle slots, successful transmissions and collisions through listening to a wireless channel without added overhead. And then, using a simple and effective method, OBEN estimates the number of nodes to set an optimal CW. Moreover, each node can adjust the CW rapidly and keeps close to the optimal value, which means they will fairly share the common wireless channel. This leads to good fairness. Through simulations, compared with the related work, OBEN achieves better fairness with almost the same throughput.

Second, based on OBEN, OBQ is proposed in single-hop network with EDCA instead of DCF. In EDCA, in addition to the problems of the conventional method DCF, there is a problem that QoS is not guaranteed enough. In EDCA, the high priority AC transmits with priority and needs to act as the high guarantee of successful transmissions. However, since the ranges of the CWs 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. The related works proposed several schemes to improve throughput in EDCA. However, the related works do not take fairness into account. OBQ aims to enhance throughput, fairness and QoS for EDCA at the same time by solving the problems of conventional method and estimating the number of nodes briefly and dynamically. In OBQ, just like OBEN, each node can estimate the number of nodes and set the optimal CW, with the result that OBQ can improve the throughput and the fairness. Furthermore, OBEN does not support QoS, while OBQ supports satisfied QoS. With the optimal CW and CW ratio according to the QoS requirement, each node sets CW for each AC separately, which leads to better QoS. When CW ratio is changed, the delay of each AC of OBQ changes but the changes of total throughput are not clearly. Even if the traffics situation of each node changes, total throughput always maintains to be high level.

Finally, based on OBEN, OBEM is proposed with DCF for multi-hop. In multi-hop wireless networks, the throughput sharply decreases as compared to single-hop when the number of nodes increases. One of the factors is the hidden node problem. The related works proposed several schemes in multi-hop wireless networks. However, they are used in limited networks and not flexible enough. Also, most works do not take the backoff process to improve the throughput. In multi-hop wireless networks, the theoretical analysis is very complicated due to the hidden node problem. The Markov model that is generally applied in theoretical analysis can not be applied. The optimal backoff process has not been studied in related works. Hence, proposed OBEM can be applied in a general environment and achieve a high throughput and good fairness. In OBEM, each node can estimate the number of neighbor nodes and hidden nodes by observing the wireless channel. Each node sets the optimal CW according to the number of nodes, which results that the collisions resulted from the hidden node problem decrease. Thus, OBEM achieved higher throughput and better fairness than the conventional method DCF.

6.2 Future work

The above proposed methods can be utilized as a distributed wireless network. Therefore, the future work will be that evaluating the proposed methods in a practice network. In a distributed wireless network, the MAC layer can be changed freely. The proposed method can be apply to the vehicle to vehicle communication and IoT (Internet of Things) networks. As shown below, another work is to try to apply the proposed methods in distributed wireless network such as vehicle to vehicle communications.

The Fig. 6.1 shows the application of the proposed method OBEN in vehicle to vehicle communications. OBEN assumes that the wireless net-

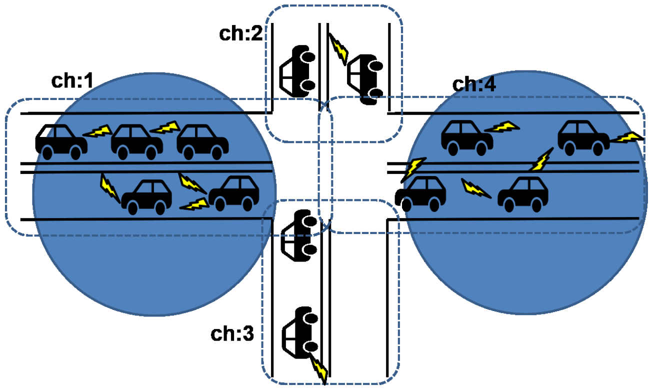


Figure 6.1: Application of the proposed method OBEN in vehicle to vehicle communication

work environment is single-hop. Hence, since each node avoids the hidden node problem, the frequency band or the channel is changed. IEEE802.11b 2.4GHz can simultaneously use 3 channels. In the real environment, it is necessary to consider the channel allocation method. The Fig. 6.2 explains the application of the proposed method OBQ in vehicle to vehicle communication. OBQ assumes that the wireless network environment is single-hop with QoS. It is the same as OBEN if the traffic of each node is only best effort. When the emergency traffic occurs from an ambulance or a patrol car, the packet is transmitted preferentially. The Fig. 6.3 shows the application of the proposed method OBEM in vehicle to vehicle communications. OBEM assumes that the wireless network environment is multi-hop. In OBEN, many finite frequencies bands and channels are required in wide wireless networks. In contrast with OBEN limited to one hop, OBEM can save the frequencies and channels in multi-hop.

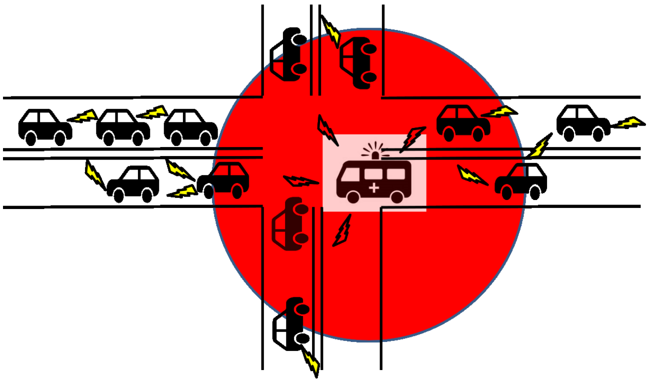


Figure 6.2: Application of the proposed method OBQ in vehicle to vehicle communication

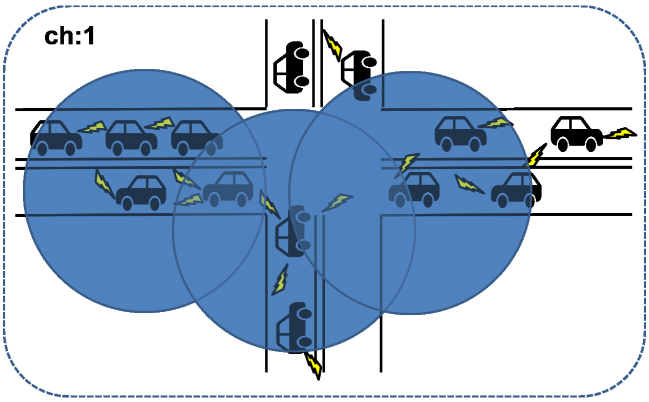


Figure 6.3: Application of the proposed method OBEM in vehicle to vehicle communication

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Author published paper

Journal paper

(1) T. Sanada, X. Tian, Q. Zhao, T. Okuda, and T. Ideguchi, “Dynamically estimating the number of wlan to improve the throughput and fairness, ” Journal of Information Processing(情報処理学会), vol. 24, no. 1, pp.64-71, 2016.

(2) T. Sanada, X. Tian, T. Okuda and T. Ideguchi, “Estimating the Number of Nodes in WLANs to Improve Throughput and QoS, ”IEICE(電子情報通信学会) TRANSACTIONS on Information and Systems, vol. E99-D, no. 1, pp.10-20, 2016.

International conference

(1) X. Tian, T. Sanada, T. Okuda, T. Ideguchi, "A Novel MAC Protocol of Wireless LAN with High Throughput and Fairness", 38th Annual IEEE Conference on Local Computer Networks, Sydney, Australia, October, 2013, pp. 688-691.

(2) T. Sanada, X. Tian, T. Okuda, and T. Ideguchi, "Improving Throughput and QoS with IEEE 802.11e," Journal of Advances in Computer Networks vol. 3, no. 2, pp. 106-113, 2015.

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