Performance Analysis of IEEE 802.11 DCF Based on OFDM

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Abstract —In order to evaluate the throughput performance of DCF about both ultra-rate and longtime delay wireless local area network (WLAN) based on Orthogonal Frequency Division Multiplexing (OFDM) modulation channel, this paper analyzes the operating principle of DCF and the throughput of system on the basis of two-dimensional Markov Model. Through theoretical analysis of the relationship among 802.11a/g throughput, the number of node and the length of data packet are acquired. Analysis, calculation and simulation are done on the influences of bit number of information carried by OFDM, free aslottime and time span of OFDM symbol on system throughput. Results of theoretical calculation and simulation testing explain that under the environment of high speed and high delay, throughput of DCF would decrease in which throughput of basic schema is generally higher than that of RTS/CTS. Furthermore, our results indicate that the longer aslotime and OFDM symbol have and the higher wireless physical channel rate is, the lower throughput of DCF is.

Index Terms—OFDM, throughput, stability, CSMA/CA, DCF, Ultra Rate WLAN

I. INTRODUCTION

Because of its flexible access way, WLAN (Wireless Local Area Network) which is based on IEEE 802.11 [1] standard is widely applied in every field of the society. With the increasing of people's requirements for real-time service in multimedia, higher request is needed in bandwidth of network and quality of service. For the purpose of adapting to market's requirement for data transmission rate, IEEE 802.11 organization respectively proposed 802.11a [2] and 802.11g [3] standards in 1999 and 2003 on the basis of combining with update of physical layer technology in which Orthogonal Frequency Division Multiplexing Technology is used in each physical layer. Here data velocity also increases from the primary 1Mbps to 54Mbps. But, comparing with physical transmission rates of 1Gbps and 10Gbps in wired network, the data rate of WLAN is very limited. For the sake of acquiring similar data transmission rate with that of wired network, wireless local area network organization IETF of IEEE began to do discussion and formulation on standard of ultra-speed WLAN in 2002. IEEE802.11n [4] Draft was released in Sept. 2009 whose standard utilized 4×4 MIMO (Multi-input Multi-output) under 20M/40M bandwidth. Its maximum data rate could reach 300Mbps. IEEE wireless local area network working team also put forward IEEE 802.11-2012 version[5] in May 2012 attempting to lead data rate of physical layer of WLAN to reach 1Gbps.

For purpose of controlling access channel of nodes, Medium Access Control Layer of WLAN based on IEEE 802.11 provides DCF (Distributed Coordinate Function) and PCF (Point Coordinate Function). However, DCF is compulsively demanded. It is a type of distributed access control mechanism on the basis of CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance). DCF defines both of access modes of basic and RTS (Request to Send)/CTS (Clear to Send) and utilizes Binary Exponential Backoff Algorithm to randomly access channel.

Bianchi G pioneered an idea of utilizing two-dimensional Markov Model to describe the access behavior process of CSMA/CA in Literature [6]. On account of his research, lots of scholars did analysis on relevant performances of DCF Protocol and proposed improvement project [7], [8]. With extensive utilization of WLAN with 802.11a/g standard, part of scholars also does analysis and research on throughput performance of WLAN under new standard [9]-[11]. However, problems of the number of bit of information carried by OFDM symbol and influence of OFDM time length on system performance are never introduced. With the increasing of rate of physical layer and improving of the number of bit of information carried by each OFDM symbol, property of CSMA/CA is worth studied. Otherwise with the development of cognitive radio technology, wireless communication technology which shares certain frequency band resource with other main users has been widely concerned. As influenced by transmission delay of channel, further research needs doing on DCF property although OFDM symbol length is high. This paper aims at doing researches on the design problems of ultra-rate physical channel and MAC Protocol of long OFDM symbol scenario.

II. PROPERTIES OF PHYSICAL CHANNEL AND LENGTH OF OFDM SYMBOL

Nowadays there exist some problems. On the one hand, resources used in wireless network communication have been less and less. On the other hand, large numbers of

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precious wireless resources are wasted. The contradiction between them may not be solved during a short time. VHF and UHF utilized in radio and television in early stage are not so widely used at present which leads precious frequency band resource to be wasted. For sake of effectively using channel resources of VHF and UHF frequency bands, dynamic spectrum sharing communication technology on account of spectrum cognitive technology has been paid extensive attention. This frequency band resource is also applied to network topology of wireless local area network whose research is strongly supported by the country.

In wireless communication, main types of radio wave propagation are space wave, refracted wave, scattered wave and other composite wave. In a multipath environment, time diffuse [12] of channel comes into being in which τ_{max} is defined as the maximum delay spread. In order to avoid ISI (Inter Symbol Interference) happening, symbol width should be much larger than the maximum delay spread of wireless channel or symbol rate should be less than the reciprocal of delay spread. In frequency domain, coherence bandwidth is defined as reciprocal of the maximum delay spread which is:

$$(\Delta B)_c \approx 1/\tau_{\max} \tag{1}$$

Parameter $(\Delta B)_c$ denotes for the frequency selection property of channel which means that channels keep the same fading characteristics in this frequency range. While mobile station communicates as it is running, its rate of receiving signal would change which is called Doppler Effect. Additional frequency offset caused by Doppler Effect could be called Doppler Shift which may be expressed with the following formula:

$$f_d = \frac{v}{\lambda}\cos\theta = \frac{vf_c}{c}\cos\theta = f_m\cos\theta \tag{2}$$

where f_c denote for the carrier frequency. C denote for velocity of light. f_m denote for the maximum Doppler shift. V denote for operating speed of mobile station. It is seen that Doppler shift and carrier frequency are in direct proportion to velocity of mobile station. In terms of time domain, another concept related to Doppler shift is coherence time namely:

$$(\Delta T)_c \approx 1/f_m \tag{3}$$

Coherence time is the statistical average value of channel impulse response keeping invariable interval. In other words, coherence time means that two arriving signals have strong amplitude correlation within a certain period of interval. If reciprocal of bandwidth of baseband signal which generally refers to the width of symbol is more than coherence time of wireless channel, waveform of signal may change which leads to its distortion and time selective fading namely fast fading. On the contrary, it would be considered as not time selective fading meaning slow fading.

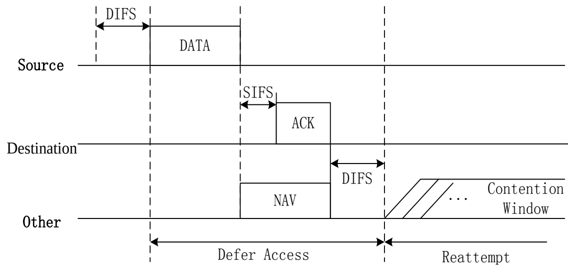
In terms of broadband services, delay spread gives rise to interloping among data symbols thus causing inter symbol interference (ISI) because data transmission rate is relatively high. With the purpose of solving this problem, physical layer applies multi-carrier modulation technique to divide the whole frequency band into several subcarriers so that they could keep mutual orthogonal. Here is the very Orthogonal Frequency Division Multiplexing (OFDM). OFDM decomposes data stream into several sub bit streams in which each sub data stream would keep much lower bit rate. Symbols with low rate and multimode coming from this type of low bit rate would modulate corresponding subcarrier thus making up a developed transmission system with multiple low-rate symbols being parallel. Among various parameters in OFDM, three parameters should be firstly determined which are bandwidth, bit rate and guard interval. Generally speaking, guard interval is 2~4 times of delay spread of wireless channel. As long as guard interval is determined, period of OFDM symbol would be ensured. In practical application, length of symbol period is generally chosen to be 5 times of guard interval because overlong period would lead OFDM system to include more subcarriers. Although this may reduce SNR loss brought by inserted guard interval, it also leads interval between subcarriers to become lower and makes system complexity be higher.

Transmission scheme of physical layer is mainly limited by requirements of users and properties of transmission channels. Under condition of users' requirements being certain and under application environment of 3Km, frequency band of radio signal may be used. On the basis of properties of DVB channel[13] actually measured by Tsinghua University, maximum delay of DVB channel could reach 27 microsecond which requires that length of cyclic prefix should be no less than 27 μs. If 3km is considered as the cell radius, its propagation delay would be 10μs. Then guard interval of switch between up and down would be 20μs at least. According to this, length of OFDM symbol in dynamic spectrum sharing wireless communication network is designed to be 250μs.

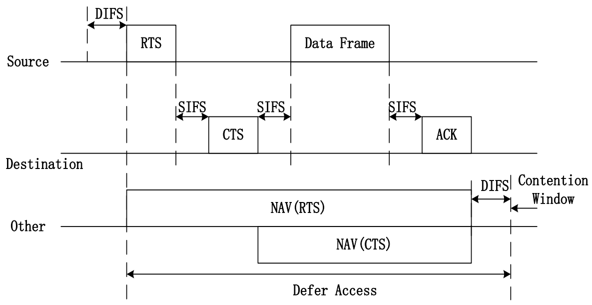
III. CSMA/CA Principle Analysis

On account of IEEE 802.11, Media Access Control (MAC) layer of WLAN utilizes DCF to finish its random access control on channel. DCF is CSMA/CA with Binary Exponential Backoff Algorithm including both transmission modes of basic and RTS/CTS. Under Basic Access Mode, network nodes directly send data. After receiving nodes correctly receive data, they return ACK frame to do confirmation with interval being SIFS (short interframe space). While under RTS/CTS Access Mode, transmitting network nodes and receiving network nodes exchange information through RTS/CTS frame on the channel to compete for the subscription occupancy right of channel and network nodes do data transmission after

RTS/CTS interaction is successfully finished. When node correctly receive MAC frame sent by other nodes, node would extract duration information on MAC frame and the occupied time length which would be told to channel. Then this time is utilized to set its network allocation vector (NAV: Network Allocation Vector). Working mechanism of IEEE 802.11 DCF is shown in Fig. 1.



(a) Basic Access Mode



(b) RTS/CTS Access Mode

Fig. 1. IEEE 802.11 MAC mechanism.

For the sake of reducing appearance of competition conflict among channel, DCF utilizes Binary Exponential Backoff (BEB) Algorithm whose analysis applies the discretization Markov chain analytical method proposed in literature [6] by Bianchi. Considering that one system keeps the fixed number of n nodes competing with each other. Length of data buffer of each network node is unlimited. There are always new packets waiting for being transmitted although one packet was successfully transmitted by node. Otherwise, all nodes have to do backspacing before packet retransmits or continuous packets transmit so as to wait for a random backspacing time. For providing convenience for research, one discrete integer pair of time is used to do label in which t and $t+1$ are supposed to be the beginning points of two continuous slots and denote for the value of Backoff counter of one given network node. Therefore Backoff count value of each node depends on its transmission history and the number of slot it going through. For convenience we suppose that, m is the maximum number of Backoff order and window Backoff maximum value is. When new packets are being transmitted, Backoff order of one node initializes to be 0 and its Backoff window is. As long as retransmission appears, it would be increased to be twice of the primary one. Use to stand for the Backoff window value of one certain node at Backoff order i . Then:

$$W_i = 2^i W, 0 \le i \le m \tag{4}$$

Then $b(t) \in (0, W_i - 1)$. Assume that random process $s(t) \in (0, \cdots, m)$ denote for the Backoff order of given network node at the moment t . Otherwise suppose that conflict probability of network node at $s(t) = i, i \in (0, m)$ is independent constant P . According to independence assumption, two dimensional discrete Markov model $\{s(t), b(t)\}$ could be used to describe Backoff process of network node. It is supposed that $Q(i,k) = \lim_{t \to \infty} P\{s(t) = i$, $b(t) = k\}$, $i \in (0, m)$, $, k \in [0, W_i - 1]$ is stable distribution of Markov chain. Then transmission probability of a given network node in one slot is:

$$\begin{aligned} \tau &= \sum_{i=0}^{m} Q(i,0) = \frac{Q(0,0)}{1-P} \\ &= \frac{2(1-2P)}{(1-2P)(W+1) + PW(1-(2P)^m)} \end{aligned} \tag{5}$$

Here $Q(i,0)$ expresses the transmission probability of Backoff counter i. $Q(0,0)$ shows the transmission probability of Backoff counter 0. So throughput of channel could be expressed as:

$$\begin{aligned} S &= \frac{P_{succ} E[P_{data}]}{P_{idle}\sigma + P_{succ} T_s + P_{coll} T_c} \\ &= \frac{P_s P_{tr} E[P_{data}]}{(1-P_{tr})\sigma + P_{tr} P_s T_s + P_{tr}(1-P_s) T_c} \end{aligned} \tag{6}$$

where P_{tr} denotes for the probability of data transmission of at least one node at certain slot. P_s denotes for the probability of successful transmission at this slot. P_{idle} denotes for the probability of channel being free. P_{succ} denotes for the probability of successful transmission of channel. P_{coll} denotes for the conflict probability of channel. Here comes:

$$\begin{cases} P_{idle} = 1 - P_{tr} \\ P_{succ} = P_{tr} P_s \\ P_{coll} = P_{tr}(1 - P_s) \end{cases} \tag{7}$$

For specifically calculating the throughput of one given mechanism in DCF, relevant parameters T_s and T_c need to be assign. T_s^{bas} and T_c^{bas} are used to respectively stand for the time of successfully transmitting packet and time of conflict consuming under Basic Access Mode.

$$\begin{cases} T_s^{bas} = H + E[P_{data}] + SIFS + ACK + DIFS \\ T_c^{bas} = H + E[P_{data}] + DIFS \end{cases} \tag{8}$$

T_s^{rts} and T_c^{rts} are used to respectively stand for the time of successfully transmitting packet and time of conflict consuming under RTS/CTS Access Mode. So:

$$S = \frac{P_{succ}.Slot}{P_{succ}.Slot + P_{idle}.Slot + P_{coll} Slot}$$

$$= P_{succ} = n\tau(1-\tau)^{n-1} \tag{9}$$

Organize Formula (6) to acquire that:

$$S = \frac{E[P_{data}]}{T_s - T_c + \frac{(1-P_{tr})\sigma / P_{tr} + T_c}{P_s}} \tag{10}$$

Among them T_s, T_c, $E[P_{data}]$ and σ are all constants. In order to acquire the maximum value of S, the following expression should be the maximum:

$$\begin{aligned} \frac{P_s}{(1-P_{tr})/P_{tr} + T_c/\sigma} &= \frac{n\tau(1-\tau)^{n-1}}{(1-P_{tr}) + T_c^* P_{tr}} \\ = \frac{n\tau(1-\tau)^{n-1}}{(1-\tau)^n + T_c^*(1-(1-\tau)^n)} &= \frac{n\tau(1-\tau)^{n-1}}{T_c^* - (1-\tau)^n (T_c^* - 1)} \end{aligned} \tag{11}$$

where $T_c^* = T_c / \sigma$ denotes the duration length of conflict which is in unit of slot. Do derivation on both sides of peer-to-peer and make it be 0. When the number of network node n is larger and τ is far less than 1, system can acquires the maximum throughput at $\tau = 1/n\sqrt{T_c^*/2}$.

IV. Influences of Information Content OFDM Carried on Throughput of DCF

A. DCF Performance Under 802.11a

IEEE 802.11a/g utilizes OFDM modulation system in physical layer in which each OFDM symbol lasts for 4us. 20MHz channel is divided into 52 effective subcarriers among which 48 subcarriers are used in data transmission and each OFDM symbol covers 216bits of data. 802.11a adds 6bit of data at the tail of data frame to show the ending of frame and 802.11g adds 6us of signal spreading in ending part of each frame. To simplify analysis, length of packet would be set to be 1000Byte without special instructions. Relevant parameters of IEEE 802.11a/g standard in this section are shown in Table I.

TABLE I: PARAMETER LIST OF IEEE 802.11A/G

Standard	Slot Time(μs)	SIFS(μs)	DIFS(μs)	Data Rate
802.11a	9	16	34	54Mbps
802.11g	9	10	28	54Mbps

Under the condition of not existing 802.11b network node, 802.11g and 802.11a keep the same properties. Therefore we just take 802.11a as example to do analysis in the following part. Encapsulation format of 802.11a data frame based on OFDM modulation technique is presented in Fig. 2.

It is seen from Fig. 2 that PLCP head length of 802.11a data frame is 20us including precursor duration 16us and SIGNAL duration 4us. Frame lengths of RTS, CTS and ACK are respective 20bytes, 14 bytes and 14 bytes. One OFDM symbol could carry 216bit of data meaning that each of them needs just one OFDM symbol.

Corresponding transmission time of each part is:

$$\begin{cases} T_{Data} = 20us + \left\lceil \frac{E[P_{data}] + 294}{R_{Data}} \right\rceil \\ T_{ACK} = T_{CTS} = T_{RTS} = 24us \end{cases} \tag{12}$$

where $\lceil x \rceil$ denotes for the minimum integral multiple of 4 which is also more than x.

In terms of RTS/CTS Access Mode, here comes:

$$\begin{cases} T_c^{rts} = RTS + DIFS = 24 + 34 = 58\mu s \\ T_c^{rts*} = T_c^{rts} / \sigma = 58/9 \approx 6.45 \end{cases} \tag{13}$$

In the same way, we acquire the following formula in terms of Basic Access Mode.

$$\begin{cases} T_c^{bas} = H + E[P_{data}] \\ \qquad = T_{data} + DIFS = 54 + \left\lceil \frac{E[P_{data}] + 294}{R_{data}} \right\rceil \\ T_c^{bas*} = T_c^{rts} / \sigma \end{cases} \tag{14}$$

Assume that K^{rts}, K^{bas} respectively stand for the $\sqrt{T_c^*/2}$ under RTS/CTS Access Mode and $\sqrt{T_c^*/2}$ under Basic Access Mode in which transmission probability of network node is $\tau = 1/(nK)$. Aiming at two modes, their values are:

$$\begin{cases} K^{rts} = \sqrt{T_c^{rts*}/2} \approx 1.8 \\ K^{bas} = \sqrt{T_c^{bas*}/2} \end{cases} \tag{15}$$

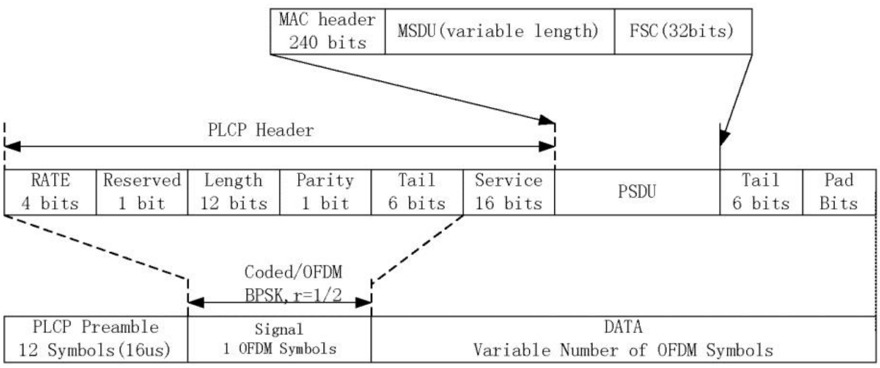


Fig. 2. Structure chart of 802.11a frame

When n is high and tends to be ∞:

$$P_{tr} = 1-(1-\tau)^n \approx 1-\left(1-\frac{1}{nK}\right)^n \approx 1-e^{-1/K}$$

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{\left(1-\frac{1}{nK}\right)^{n-1}}{K\left(1-e^{-1/K}\right)} \approx \frac{e^{-1/K}}{K\left(1-e^{-1/K}\right)} \quad (16)$$

Maximum throughput of system is:

$$S_{\max} = \frac{E[P_{data}]}{T_s - T_c + \frac{(1-P_{tr})\sigma / P_{tr} + T_c}{P_s}} = \frac{E[P_{data}]}{T_s + K\sigma + T_c\left(K\left(e^{1/K}-1\right)-1\right)} \quad (17)$$

When parameters shown in Table I are used and data length is 1000 bytes, we acquire the parameter values calculated under Basic Access Mode and RTS/CTS Access Mode shown in Table II.

TABLE II: RELEVANT PARAMETER VALUES UNDER TWO MODES

MAC Mechanism	Basic	RTS/CTS
Data length(Byte)	1000	1000
Data Transmission Times $E[P_{data}]$ (us)	176	176
Successfully Transmission times T_s (us)	250	330
Collision Times T_c (us)	210	58
Idle slot time σ (us)	9	9
$T_c^* = T/\sigma$	23.3	6.45
$K = \sqrt{T_c^*/2}$	3.42	1.8

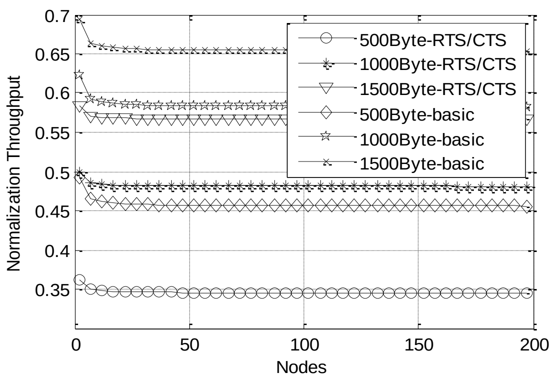


Fig. 3. Maximum theoretical throughput versus node

Utilizing calculation and analysis tool MATLAB, we acquire the maximum theoretical throughputs under conditions of different network nodes, environments of both data lengths of 1000 bytes and 1500 bytes and 802.11a/g being under both modes of basic and RTS/CTS shown in Fig. 3.

For further comparing influences of network node and database data length on maximum throughputs of system under both modes of basic and RTS/CTS, maximum theoretical throughputs under different data lengths and network nodes are expressed in Table III.

TABLE III: COMPARISON TABLE OF MAXIMUM THEORETICAL THROUGHPUTS

Node	RTS/CTS mode Theoretical Throughputs			Basic mode Theoretical Throughputs		
	Data(Byte)			Data(Byte)		
	500	1000	1500	500	100	1500
2	0.361	0. 50	0.584	0.493	0. 622	0.693
5	0.351	0. 488	0.573	0.469	0. 597	0.669
10	0.348	0. 484	0.570	0.462	0. 590	0.661
20	0.347	0. 483	0.568	0.459	0. 586	0.657
30	0.346	0. 482	0.568	0.458	0. 585	0.656
40	0.346	0. 482	0.567	0.457	0. 584	0.655
50	0.346	0. 482	0.567	0.457	0. 584	0.655
100	0.345	0. 482	0.567	0.456	0. 583	0.654

It is seen from Fig. 3 and Table III that property of RTS/CTS Access Mode is lower than that of Basic Access Mode under IEEE 802.11a/g standard when data length is less than 1500 bytes. The shorter data length is, the lower RTS/CTS property becomes. As most networks nowadays are based on Ethernet whose MAC frame length is less than 1518 bytes. Under this type of condition, RTS/CTS property is lower than that of Basic Access Mode. The main reason is that 802.11a applies OFDM modulation technique leading its data rate to increase and making time of transmitting effective data decrease. While influenced by channel performance, time of slotted being free and transmission time of RTS and CTS frames basically keep unchanged thus giving rise to the reduction of channel throughput.

For sake of testing the actual performance of MAC protocol of WLAN based on IEEE 802.11a, MATLAB is utilized to do simulation on channel throughput under RTS/CTS and Basic Access Modes. Table IV shows the simulation parameter values in which conflict avoidance process applies Binary Exponential Backoff Algorithm. Here minimum window of system is $CW_{\min} = 32$ and maximum Backoff window value is $CW_{\max} = 1024$. Simulation results are seen in Fig. 4, Fig. 5 and Fig. 6.

TABLE IV: TABLE OF SIMULATION PARAMETER VALUES

Mode	Slot Time	SIFS (μs)	DIFS (μs)	RTS (μs)	CTS (μs)	ACK (μs)
RTS/CTS	9μs	16	34	24	24	24
Basic	9μs	16	34			24

Fig. 4 is the comparison diagram between simulation result and theoretical analysis result of RTS/CTS Access Mode. Fig. 5 is the comparison diagram between simulation result and theoretical analysis result of Basic Access Mode. Fig. 6 is the simulation diagram of influences of nodes on system throughputs under both modes. Results of both simulation diagrams show that throughputs acquired through system simulation are less than theoretical maximum throughputs. Both results of theoretical calculation and simulation show that the longer packet is, the bigger throughput becomes. In theoretical analysis results, channel throughput is mostly influenced by data length. When the number of network node is high, channel throughput basically remains unchanged. Simulation results in Fig.6 show that system throughput is not only influenced by data length but also affected by its relationship with network node number. The larger node number is, the lower channel throughput is. Comparing with RTS/CTS Access Mode, Basic Access Mode is more influenced by network nodes.

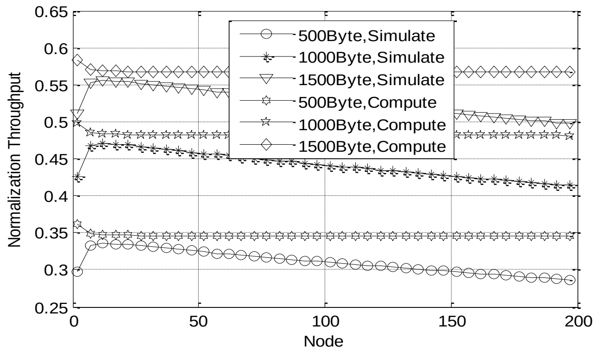


Fig. 4. Comparison between simulation and theoretical values of RTS/CTS access mode

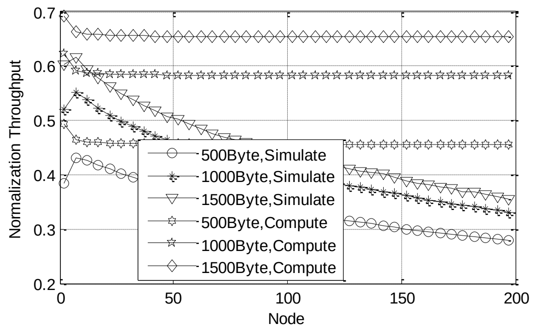


Fig. 5. Comparison between simulation and theoretical values of basic access mode.

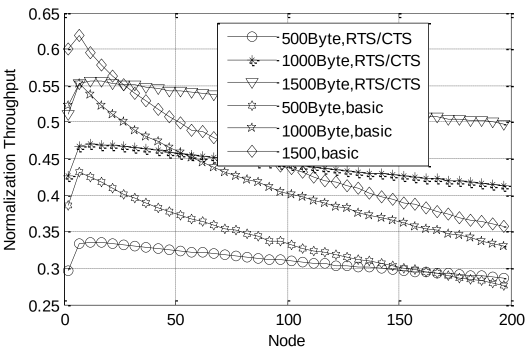
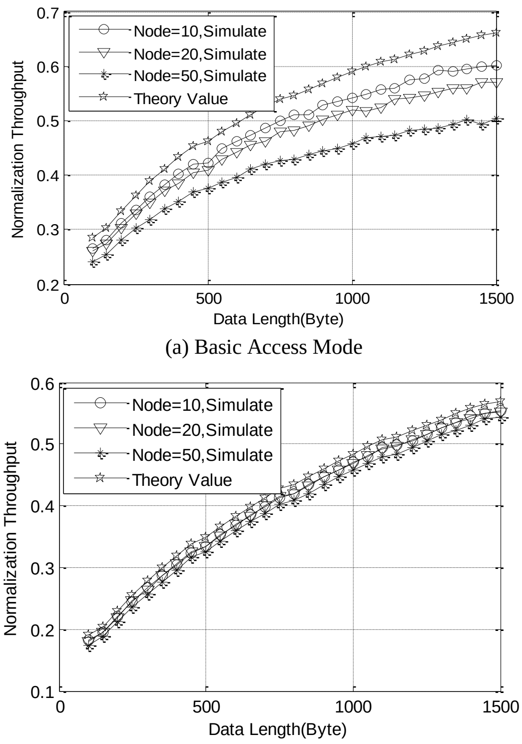


Fig. 6. Simulation throughputs versus Node

In theoretical analysis, throughput tends to be a limiting value with the increasing of network node whose main reason is that transmission probability of system is a certain constant value in theoretical analysis. Simulation results express that practical throughput of system has a lot to do with the number of network node. In actual system, each successfully transmitted network node sets its backoff counter to be minimum window CW_{min}. While after conflict happens, network node involved in the conflict needs to double its backoff window which leads high gap to come into being among transmission probabilities of each network node. In the initial state each mobile network node randomly chooses an access slot. As all network nodes equiprobably and randomly choose access slots, selected probabilities of slots in channel are the same. When system is stable, probability distributions of each selected slot would be seriously uneven[14] which also results in the increasing of conflicting probability of system thus leading system throughput to decrease.

With the purpose of measuring the influences of data length on throughput under Basic Access Mode and RTS/CTS Access Mode, simulation verification is done on MATLAB platform whose results are presented in Fig. 7(a) and Fig. 7(b). Both simulation result and theoretical count show that the longer packet is, the higher channel throughput is.



(a) Basic Access Mode

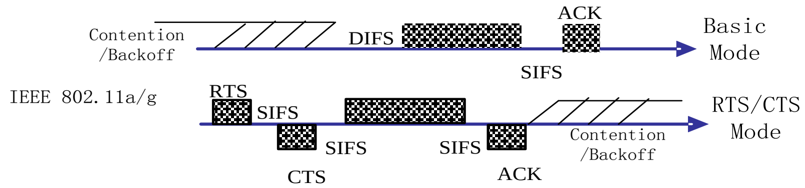
(b)RTS/CTS Access Mode

Fig. 7. Throughput versus Data Length under Both Access Modes

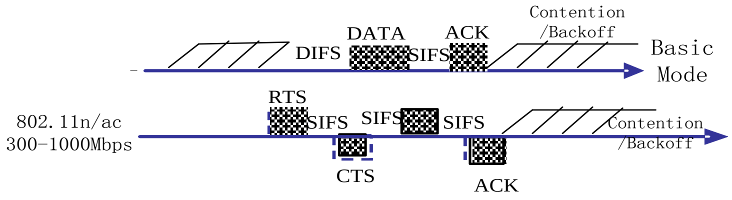
B. *Throughput of Ultra Speed WLAN*

IEEE 802.11n physical layer utilizes channel aggregation technique in which two 20MHz channels are united into one 40MHz channel and two 40MHz channels could also be united into one 80MHz channel. 802.11n raises subcarrier number of data transmission up to 52 and binds two 20MHz channels to be a 40MHz one leading available subcarrier number to become 108 through which each OFDM symbol could carry 648bit of information using 4×4 antenna and channel rate would reach 540Mbps utilizing 5/6 encoder. If physical layer applies spectrum aggregation reaching up to 80MHz and SU–MIMO (Simple-User MIMO) and MU-MIMO (Multi-User MIMO) techniques up to 8×8, channel transmission rate would pass 1Gbps.

It is shown in Fig. 8 that although rate of physical layer improves 10 times even up to 1Gbps, system throughput could never get prominent improvement still using CSMA/CA mechanism. In order to solve the problem of concealing network nodes, RTS/CTS frame transmission needs to utilize the same way with 802.11a/g whose time is about 24μs. Otherwise for realizing the detection of channel condition, SIFS and DIFS values have to stay the same with 802.11a/g meaning that only transmission rate of data improves in the whole system. It is known from (6) that the improvement of rate of physical layer just reduces numerator part $P_s P_{tr} E[P_{data}]$ and denominator $P_{tr} P_s T_s$. As we see from Fig.8 (b) that proportion of transmitting effective data decreases with the increasing of transmission rate, IEEE 802.11n standard proposes to apply frame aggregation to enhance channel throughput.

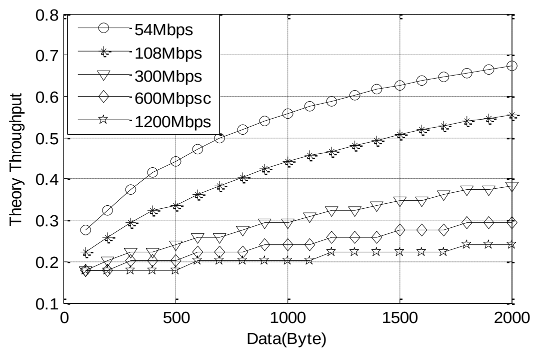


（a） IEEE 802.11 DCF Mechanism

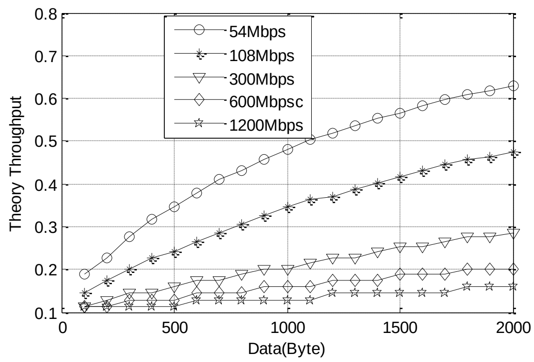


(b) Ultra-Rate WLAN DCF Mechanism

Fig. 8. Performance of DCF under Ultra versus Low-Speed



(a) Basic Access Mode



(b) RTS/CTS Access Mode

Fig. 9 Maximum Theory Throughput versus Packet Length.

C. Throughput of Various Transmission Rate

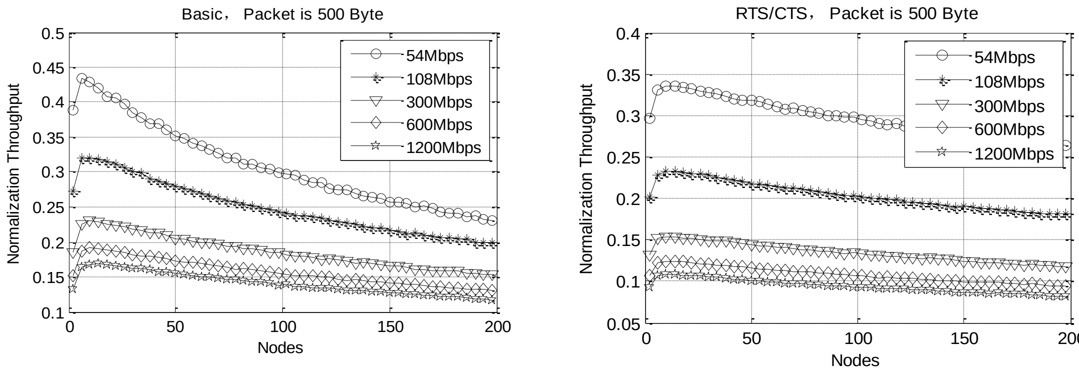
In order to analyze the effect of channel utilization resulted from the data packet length P_{data} , calculate the throughput with 5 different data rates in both Basic and RTS/CTS mode using MATLAB tool. The data packet length varies from 100 to 2000 bytes. The results are shown in Fig. 9 in which (a) shows the relationship between the Basic-based data packet length and the maximal throughput, (b) shows the relationship between the RTS/CTS-based data packet length and the maximal throughput.

It is clear that the longer is the data packet, the higher is the throughput. But, the throughput increases slowly when the physical layer data rate gets faster. We can see from Fig. 9, the both of throughputs with two kinds of mode is not greater than 0.3 even if the data rate of physic layer exceeds 600Mbps and the data packet length equals 2000 bytes which is less than the maximum of time-slot ALOHA. When the data rate exceeds 100 Mbps, the throughput of Basic mode is greater than RTS/CTS's. According to the approximately formula (17), the maximum theoretic throughput is independent of the number of nodes in system. But formula (17) indicates the reverse results that the throughput of system can get maximum when nodes send data by the probability of $\tau = 1/n\sqrt{T_c^*/2}$.

For studying the DCF performance of BEB control algorithm, we make the simulation by MATLAB platform. The parameters of simulation scenario are set as follows: 1) the data rates of physical layer are set respectively as: 54 Mbps, 108 Mbps, 300 Mbps, 600 Mbps and 1.2 Gbps; 2) the related parameters of system are set as Table I; 3) the data packet length are set respectively as: 500 bytes, 1000 bytes and 1500 bytes.

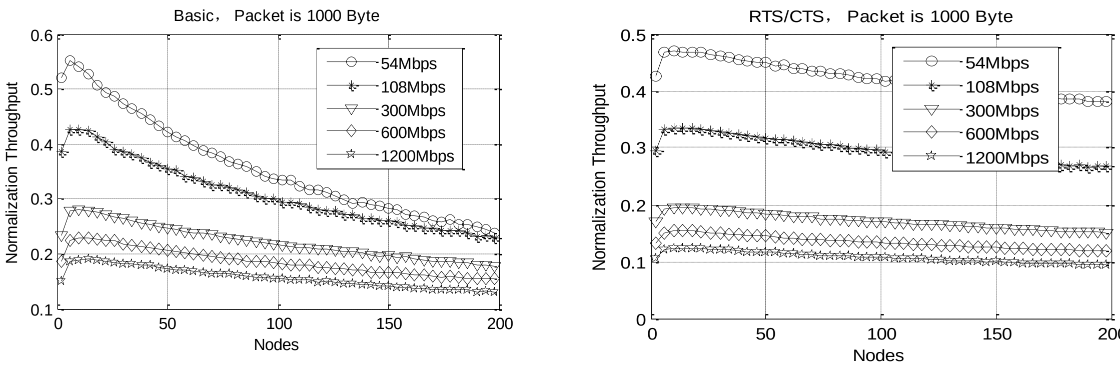
The simulation results are shown in Fig. 10, Fig. 11 and Fig. 12, which show respectively the DCF throughput of the data packet length of 500 bytes, 1000 bytes and 1500 bytes.

The simulation results are shown in Fig. 10, Fig. 11 and Fig. 12, which show respectively the DCF throughput of the data packet length of 500 bytes, 1000 bytes and 1500 bytes. These results indicate that: 1) either in RTS/CTS mode or Basic mode, the throughput must go through an ascending process during the nodes vary from 2 to 100 and get the maximum as the moment of 16 nodes and have a decline as the increase of the number of nodes. The reason is that the size of competition window is updated to the minimum value of 32 by the node after successful sending data. 2) Comparing with RTS/CTS mode, there is greater effect in Basic mode, especially the bigger is the number of node, the more decline is the throughput. 3) The longer is the data packet length, the higher is the throughput of system. We must make greater the data packet length to improve the throughput performance of system. 4) Under both of modes, the higher is the data rate of physical layer; the lower is the system throughput. The system throughput is less than 0.3 if the data rate of physical layer exceeds 300 Mbps, even if the data packet length equals 1500 bytes. This result denotes that the method is no longer applicable to improve the system throughput by setting the length of the data packet much greater than the control frame's with the increase of the rate of physical layer. When the rate of physical layer reaches a certain degree, the OFDM-based transmission mechanism reduces as the time slot competition access mechanism, and the system throughput is also less than the performance of the time-slot ALOHA.



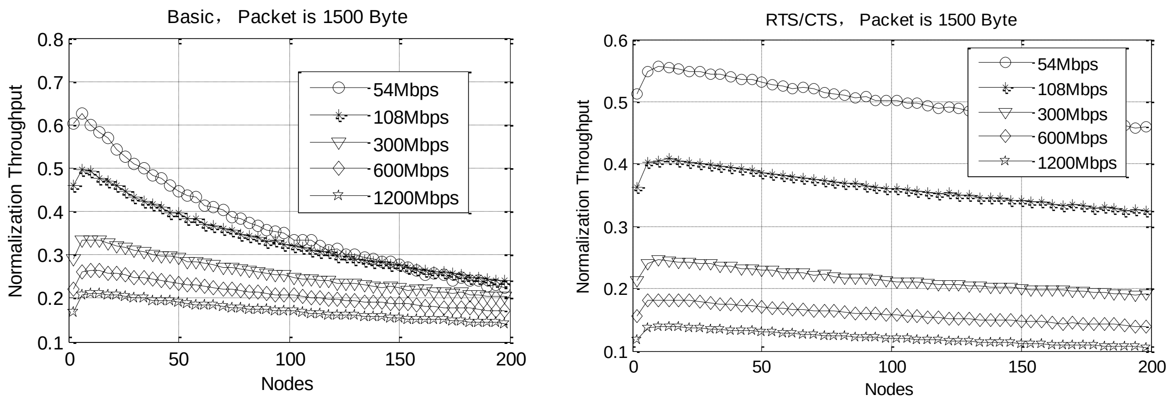
(a) Basic Access Mode (b)RTS/CTS Access Mode

Fig. 10. DCF Throughput on packet length is 500Bytes



(a) Basic Access Mode (b) RTS/CTS Access Mode

Fig. 11. DCF Throughput on packet length is 1000Bytes



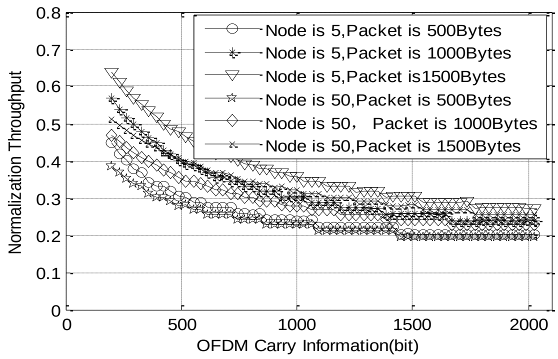
(a) Basic Access Mode (b)RTS/CTS Access Mode

Fig. 12. DCF Throughput on packet length is 1500Bytes

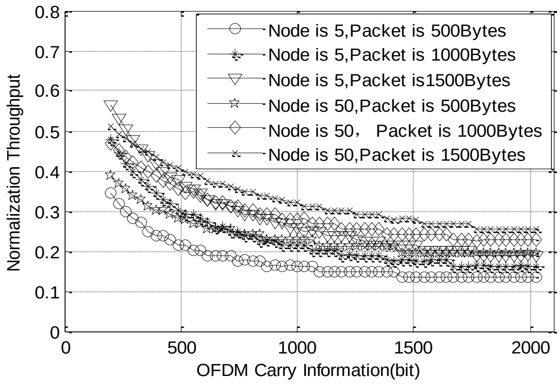
D. Throughput of OFDM Symbol Carry Information Bits

To test channel throughputs of OFDM symbol carrying different information bits, we respectively do simulations on scenarios with 5 and 50 network nodes and conditions of 500Byte, 1000Byte and 1500Byte data lengths.in which, the time of OFDM symbol is 4us. Channel throughputs of CSMA/CA under RTS/CTS Access Mode and Basic Access Mode are respectively shown in Fig. 13 (a) and (b) from which we can see that the more information bit each OFDM symbol carries, the lower channel throughput would be. Under the condition of OFDM symbols carrying the same information bit, the bigger data length is, the higher channel throughput is. From Fig. 13 (a) we know that network nodes keep lower influences on throughput under RTS/CTS Access Mode. On the contrary, it keeps higher influences on throughput under Basic Access Mode as shown in Fig. 13 (b).

In addition, we see from Fig. 13 that channel throughput under RTS/CTS Access Mode is less than that under Basic Access Mode when data bit carried by OFDM symbol is more than 500bit. When data bit it carries passes 1000bit, channel throughputs of both modes are less than 0.368.



(a) Basic Access Mode



(b) RTS/CTS Access Mode

Fig. 13. Channel Throughput versus information bit carried by OFDM symbol.

We have also tested influences of network node on channel throughput under broadband environment and done simulation aiming at the following scenarios. Scenarios parameters are set as follows: (1) data transmission rates of physical channel are 108Mbps, 300Mbps, 540Mbps and 1Gbps. OFDM symbol time is still 4us. Then information bits each OFDM symbol could carry are 432bit, 1200bit, 2160bit and 4000bit. (2) Other parameters are set the same with IEEE 802.11a which are seen in Table I. (3) Data lengths are 500Byte, 1000Byte and 1500Byte. Utilize MATLAB simulation platform to acquire simulation results shown in Fig. 14. It is show that both channel throughputs of RTS/CTS Access Mode and Basic Access Mode go through a rising process and then begin to decline during the process of network node number changing from 2 to 50. Under both modes, the more number of information bit each OFDM symbol carries, the lower throughput channel keeps.

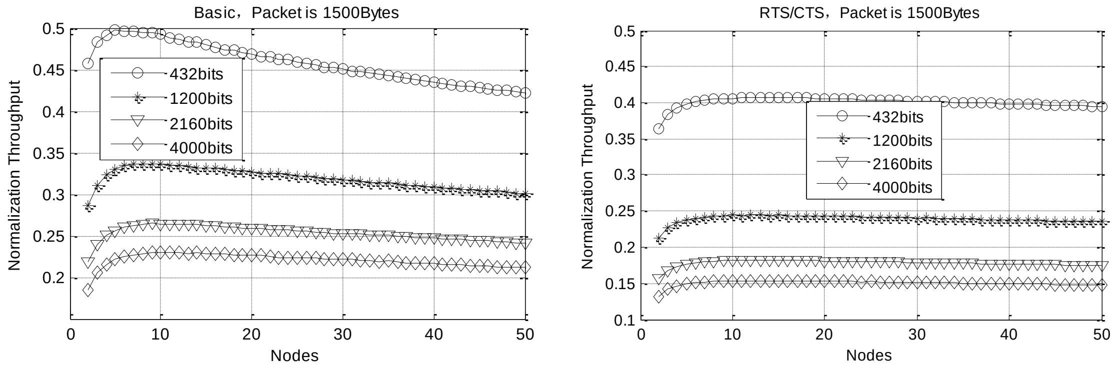
According to packets of statistical data[15] transmitted on American MCI backbone network and integrated data statistics[15] on Sprint backbone network by Chuck Farleigh and others, about 60% percent of packets are of 44Byte long meaning that the carried data by them is confirmation message segment of TCP. Packets whose length is from 44 to 500Byte cover about 15% approximately obeying uniform distribution. About 15% of packets keep length of about 576Byte namely the default length of IP datagram. About 10% of packets' lengths are 1500Byte. The number of packets passing 1500Byte is little.

Based on the distribution function of network data length in literature [15], mathematical expectation of data length in network transmission is about:

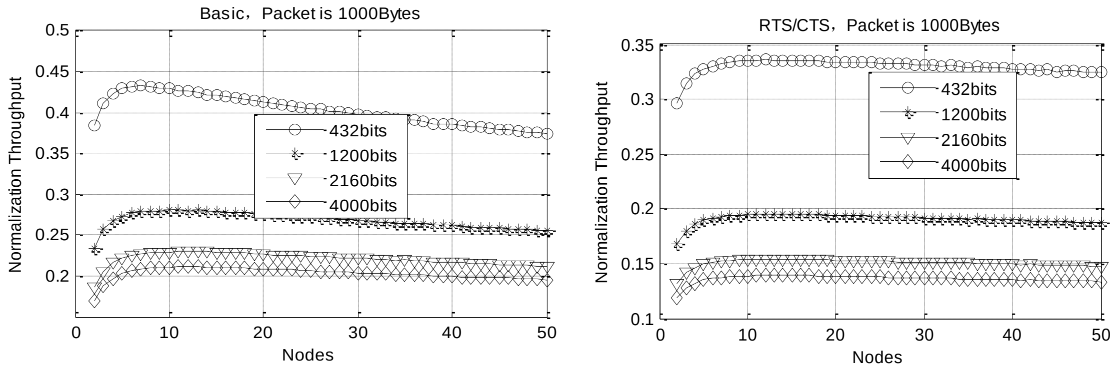
$$E[Packet\_size] \approx 44*0.1+272*0.15 \\ +576*0.15+1500*0.1 \approx 282(Byte) \tag{18}$$

It is seen from results of Formula (18) that average length of packet transmitted in network is low which about 282 Bytes (2256 bits) is. When rate of physical layer reaches 600Mbps, OFDM symbol with 4us of time length may be used to carry 2400bit of data. This explains that the vast majority of data needs only one OFDM symbol. Even one OFDM symbol could carry information of multiple packets. Fig. 14(c) describes that under the condition of data length being less than 500Byte, utilization rate of channel is very low and its effective throughput is less than 0.35 no matter it is under RTS/CTS or Basic Access Mode and whatever the number of network node of system is. When each OFDM symbol carries more than 2000bit of information, channel throughput rate of CSMA/CA protocol under RTS/CTS Access Mode is less than 0.16 and that of Basic Access Mode is also lower than 25%.

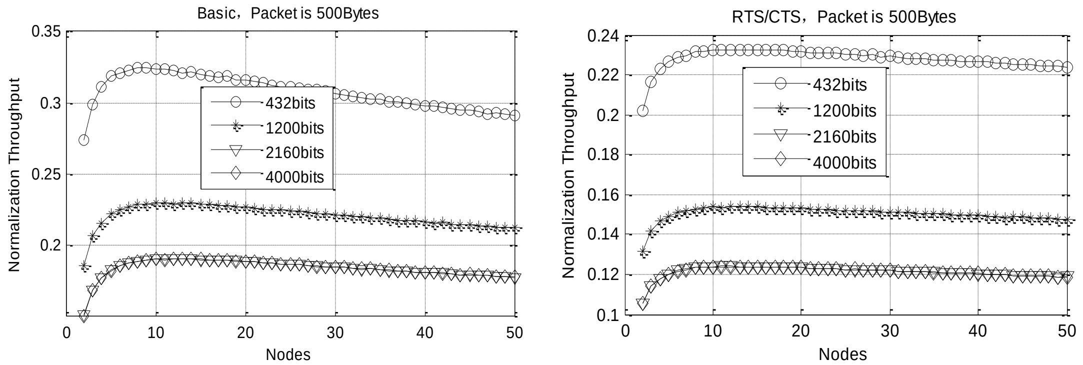
Simulation results above present that utilization rate of channel is quite low without changing MAC access mechanism based on 802.11a/g under broadband WLAN environment because each OFDM symbol has to carry a lot of information under this type of condition. Therefore the enhancing of physical layer rate could never help to improve utilization rate of channel without more efficient MAC protocol.



(a) Throughputs of Both Modes under 1500Byte of Data



(b) Throughputs of Both Modes under 1000Byte of Data



(c) Throughputs of Both Modes under 500Byte of Data

Fig. 14. Throughput versus OFDM symbol length.

V. Influences of OFDM Symbol Property on CSMA/CA Throughput

The current WLAN physical spectrum mainly utilizes 2.4GHz such as 802.11 and 802.11b/g and 5GHz spectrum such as 802.11a. Influenced by channel fading and multipath effect, covering radius indoor of WLAN using AP is theoretically 100m and that outdoor is 300m. While Dynamic Spectrum Sharing Wireless Network (DSSWCS) based on spectrum cognitive technology[16] makes use of 694—806MHz wireless spectrum resource of public television network to realize the wireless access of low-speed mobile network nodes within the radius of 3Km. Referring to properties of DVB channel actually measured by Tsinghua University, the maximum delay of channel could reach 27μs requiring that CP length has to be no less than 27μs. According to properties of OFDM symbol, its length is basically 5 times of CP. Therefore OFDM symbol length is 135μs at least. Moreover transmission delay of 3Km covering radius is 10μs and transmission loopback time is 20μs. In WLAN standard, SIFS and aSlottime are defined as follows:

$$\begin{aligned} \text{aSIFSTime} &= \text{aRxRFDelay} + \text{aRxPLCPDelay} \\ &+ \text{aMACProcessingDelay} \\ &+ \text{aRxTxTurnaroundTime} \\ \text{aSlotTime} &= \text{aCCATime} + \text{aRxTxTurnaroundTime} \\ &+ \text{aAirPropagationTime} \\ &+ \text{aMACProcessingDelay} \end{aligned} \tag{19}$$

On the basis of (19) and channel properties in application scene, SIFS in dynamic spectrum sharing wireless network is more than 54μs at least and length of slot aSlottime is no less than 64μs. Here length of slot means the unit time σ which is acquired through network node detecting free channel and subtracting 1 from count value in random backoff mechanism.

Based on $K=\sqrt{T_c^*/2}=\sqrt{T_c/2\sigma}$ defined by (15), expression (17) of maximum theoretical throughput of channel could be rewritten as follows:

$$S_{\max}=\frac{E[P_{data}]}{T_s+K\sigma+T_c\left(K\left(e^{1/K}-1\right)-1\right)}$$
$$=\frac{E[P_{data}]}{T_s+\sqrt{T_c/(2\sigma)}\sigma+T_c\sqrt{T_c/(2\sigma)}\left(e^{1/\sqrt{T_c/(2\sigma)}}-1\right)-T_c} \quad (20)$$

When $\sqrt{T_c/(2\sigma)}>1$,

$$\sqrt{\frac{T_c}{2\sigma}}\left(e^{1/\sqrt{T_c/(2\sigma)}}-1\right)\approx\sqrt{\frac{T_c}{2\sigma}}\left(1+\frac{1}{\sqrt{T_c/(2\sigma)}}+\frac{\sigma}{T_c}-1\right) \quad (21)$$
$$=1+\sqrt{\sigma/(2T_c)}$$

Formula (20) may be expressed as:

$$S_{\max}\approx\frac{E[P_{data}]}{T_s+\sqrt{T_c\sigma/2}+T_c\sqrt{\sigma/(2T_c)}}=\frac{E[P_{data}]}{T_s+\sqrt{2T_c\sigma}} \quad (22)$$

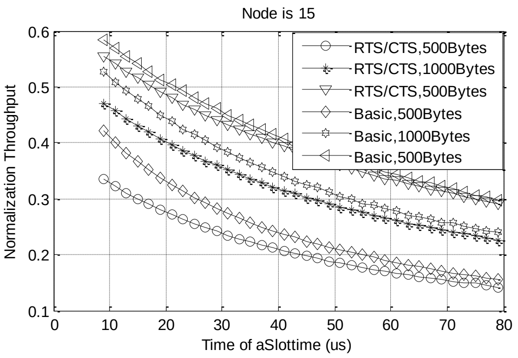


Fig. 15. Influences of aslottime on throughput.

On the basis of Formula (22), system maximum throughput is inversely proportional to slot σ in which maximum theoretical throughput of system decreases with the increasing of σ. To measure the influences of slotted time σ on channel throughput, MATLAB simulation platform is utilized to do simulation testing on channel throughputs under different σ. Parameters of simulation scene are set as follows: (1) Physical layer still utilizes OFDM modulation type. (2)Data rate is 54Mbps. (3) Data lengths are divided into three types: 500bytes, 1000bytes and 1500bytes. (4) Network node number is 15. Simulation results are presented in Fig. 15.

Simulation results in Fig. 15 present that no matter it is under RTS/CTS or Basic Access Mode, the longer aSlottime is, the lower throughput would be. Under the same mode, the longer packet is, the higher channel throughput becomes.

Influenced by channel multipath effect and Doppler shift, all of aSlottime, SIFS and OFDM symbol length would be affected. Specific values of the three parameters are determined by physical layer. Firstly, suppose that SIFS and aSlottime are both the same with 802.11a and data rate is determined to be 20Mbps. According to Formula (12), the time of frame transmission is:

$$\begin{cases}T_{Data}=20+\left\lceil\frac{E[P_{data}]+294}{S_{ofdm}}\right\rceil*T_{ofdm}\\ T_{ACK}=T_{CTS}=T_{RTS}=20+T_{ofdm}*N_{ofdm}\end{cases} \quad (23)$$

where T_{ofdm} is time length of OFDM symbol. N_{ofdm} is the number of OFDM symbol. S_{ofdm} is the information bit number of carried by each OFDM symbol.

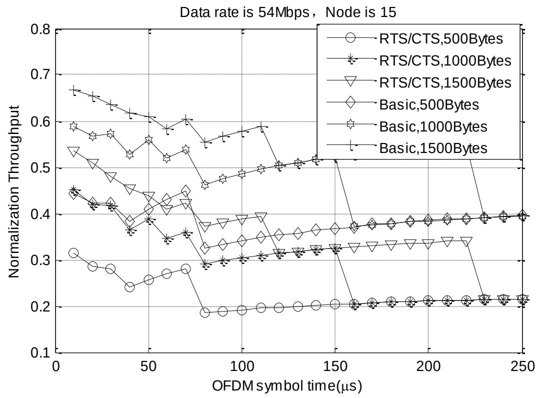


Fig. 16. Throughput vs. OFDM Symbol Length.

Under MATLAB platform simulation is done on the relationship between OFDM symbol length and system throughput. Parameters of simulation scene are set as follows: 1) Data rate is 20Mbps. 2) Data lengths are divided into three types of 500bytes, 1000bytes and 1500bytes. 3) Network node number is 20. 4) Other parameters without relationship with OFDM symbol length keep the same with 802.11a. Simulation results are seen in Fig. 15 which present that the bigger data length is, the higher throughput is. Throughput declines in steps and several inflection points come into being with the increasing of OFDM symbol length under both modes. This is because data rate in simulation is certain while information bit carried by OFDM symbol would increases with the improving of OFDM symbol length in which throughput is calculated based on proportion of transmission data.

Comparing the simulation results of Fig. 16 (a) and (b), we see that throughput of Basic Access Mode is higher than that of RTS/CTS under the condition of both data lengths and information bits OFDM symbol carrying keeping the same. Combining with influences of aSlotime on system properties in Fig. 16, we know that DCF property is lower when transmission delay of channel is higher.

VI. CONCLUSIONS

With the increasing of physical layer rate, channel throughput of RTS/CTS Access Mode declines and its property is lower than that of Basic Access Mode because

RTS, CTS and ACK frames interact in RTS/CTS Access Mode. Meanwhile each OFDM symbol could carry 4000bit of information when rate of physical layer reaches up to 1Gbps leading a vast majority of data in the current network to be successfully transmitted and making data transmission time be less than slot time. Otherwise time of aslottime and OFDM symbol keeps quite long because of some special environments and influenced by channel transmission properties which leads CSMA/CA protocol based on IEEE 802.11 standard to fail to cater for environment. Under both of modes, the higher is the data rate of physical layer, the lower is the system throughput. The system throughput is less than 0.3 if the data rate of physical layer exceeds 300 Mbps, even if the data packet length equals 1500 bytes. This result denotes that the method is no longer applicable to improve the system throughput by setting the length of the data packet much greater than the control frame's with the increase of the rate of physical layer. When the rate of physical layer reaches a certain degree, the OFDM-based transmission mechanism reduces as the time slot competition access mechanism, and the system throughput is also less than the performance of the time-slot ALOHA.

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