國 立 交 通 大 學

電 信 工 程 學 系 碩 士 班

碩 士 論 文

飽和訊框匯集無線區域網路通道使用率分析

A Channel Utilization Analysis for the Saturated WLAN with Frame Aggregation

研究生　：宋政家

指導教授：李程輝 教授

中 華 民 國 九 十 五 年 六 月

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A Thesis
Submitted to Department of Communication Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science
in
Communication Engineering
June 2006
Hsinchu, Taiwan, Republic of China.

中 華 民 國 九 十 五 年 六 月

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中文摘要

以 IEEE 802.11 為基礎的無線區域網路已經廣泛地被應用到區域的高速資料存取。IEEE 802.11 MAC 提供了一種可以讓多個使用者去分享無線媒介的方法，無論負載被傳送地多麼快，通道使用率都會因為負載的管理位元而被限制住。為了要增加通道使用率，訊框匯集是一種增加效能的直覺方法。這篇論文提供了一種分析的方法去估計在飽和無線區域中的通道使用率，分析的模型是以 RTS/CTS 為基礎的競爭存取機制加上單向的訊框匯集或是雙向的訊框匯集。這篇論文也提供了一種更加準確的分析方法去估計媒介中兩次傳送之間的延後時間。

這個分析方法是以平均值為估算的原則，模擬結果顯示出我們分析的方法是比其他論文更加準確的。。

A Channel Utilization Analysis for the Saturated WLAN with Frame Aggregation

Student: Cheng-Chia Sung Advisor: Prof. Tsern-Huei Lee

Department of Communication Engineering
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Abstract

The IEEE 802.11-based wireless LAN has been widely deployed for local area high-speed data access. The IEEE 802.11 MAC provides a method for multiple users to share the wireless media. The channel utilization is limited because of protocol overhead no matter how fast the payload is transmitted. To increase utilization, frame aggregation is a straightforward way to improve the efficiency. This thesis presents an analytic method to estimate the utilization in the saturated WLAN for RTS/CTS-based contention access mechanism with unidirectional or bidirectional aggregation. This thesis also presents a more precise estimation for the backoff time between two transmissions in the medium.

This analytic method uses the principle of average value approximation. The simulate results show that our analytic method is more accurate than other papers.

誌謝

首先要感謝我的指導教授–李程輝老師，這兩年來的諄諄教誨與細心指導，讓我學習到作研究上應有的態度與方法。也感謝老師給予我自由的研究空間，可以朝自己有興趣的研究方向鑽研。

接下來要感謝實驗室的景融學長、耀文學長、德功學長、郁文、迺倫、紹瑜、泓霖、紹喜，在我作研究上發現問題時可以有討論的對象，也給予我精神上的鼓勵與支持。感謝實驗室學弟，嘉旂、登煌、建成、柏庚生活上的協助與幫忙。還要感謝我的好朋友們，很高興這兩年來有你們陪伴與參與，不管是快樂或是悲傷的事情，我想多年後，都將成為你我回憶中美好的一部份。

感謝父親宋天賜先生與母親陳鳳英女士從小到大的照顧與栽培，讓我可以安心地讀書，也教導我做人做事的道理。感謝已經過世的爺爺與奶奶，雖然您們已經不在身邊，但是您們疼愛我的身影會永遠留在我的心中。感謝我的哥哥、姐姐與關心我的親戚們，對我生活上的關心與支持。

謹將此論文獻給所有關心我的人

2006 年 6 月 於風城交大

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Acronym

AC	Access Category
AIFS	Arbitration Interframe Space
AP	Access Point
BSS	Basic Service Set
CA	Collision Avoidance
CAP	Controlled Access Phase (Period)
CCK	Complementary Code Keying
CD	Collision Detection
CDF	Cumulative Distribution Function
CF-Poll	Contention Free Polling Frame
CFP	Contention Free Period
CP	Contention Period
CSMA	Carrier Sense Multiple Access
CTS	Clear to Send
CW	Contention Window
DCF	Distributed Coordination Function
DIFS	DCF interframe space
DSSS	Direct Sequence Spread Spectrum
EDCF	Enhanced Distributed Coordination Function
EDCA	Enhanced Distributed Channel Access
HC	Hybrid Coordinator
HCCA	HCF Controlled Channel Access
HCF	Hybrid Coordination Function
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific, and Medical
MAC	Medium Access Control
MPDU	MAC Protocol Data Unit
MSDU	Mac Service Data Units
NAV	Network Allocation Vector
OFDM	Orthogonal Frequency Division Multiplexing
PIFS	PCF interframe space
PC	Point Coordinator
PCF	Point Coordination Function
QoS	Quality of Service

RTS	Request to Send
SIFS	Short Interframe Space
STA	station
TBTT	Target Beacon Transition Time
TC	Traffic Category
TS	Traffic Stream
TXOP	Transmission Opportunity
WLAN	Wireless Local Area Network

Chapter 1

Introduction

In the recent years, the wireless local area network (WLAN) becomes more important in our life. If devices are connected to the network by a cable line, their movement must be reduced dramatically. Wireless connectivity can provide users more freedom to use the mobile devices anywhere, ex. on the campus, at home, or in the coffee shops. IEEE 802.11 has been widely deployed in WLAN to provide wireless and broadband network access to mobile devices.

The goal of this thesis is to establish an analytic model for the channel utilization and the backoff time between two transmissions in the medium in a saturated WLAN that supports frame aggregation. The saturated WLAN supports two scenarios (1) unidirectional traffic flow (See Fig.4-1 and Fig.4-2) (2) bidirectional traffic flow (See Fig.5-1 and Fig. 5-2).

It is called aggregation to allow multiple MAC frames to be carried in a single physical frame. This new feature is developed by the 802.11n task group. In order to simplify our analysis, we suppose only one aggregate in each direction (See Fig. 4-2 and Fig. 5-2). The original scenario is Fig.1-1.

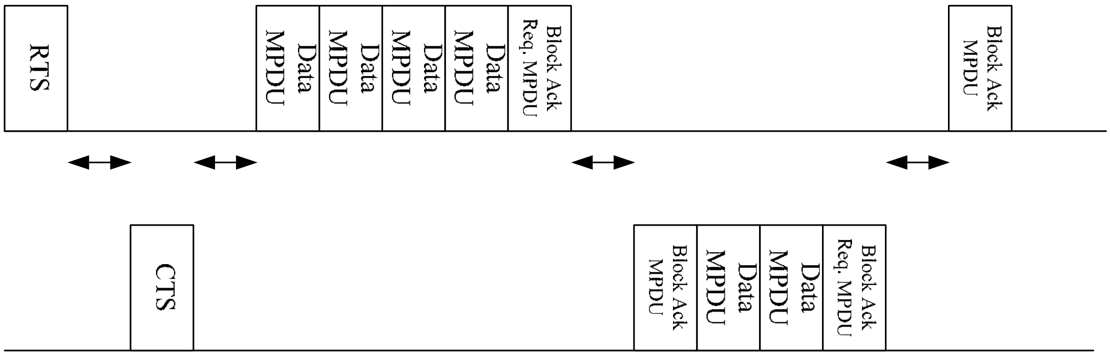

Fig.1-1 original bidirectional aggregation in a WLAN

RTS/CTS-based contention access mechanism is used in our scenario because it can reduce the collision cost. Because an aggregated frame usually has a larger frame size. In our scenario, the frame transmission is reliable, except for losses caused by the RTS collision.

We also suppose there are N stations (including the AP) in the saturated WLAN that have an equal probability $\frac{1}{N}$ that contend for the channel successfully. The definition of a saturated WLAN is described in the beginning of the chapter 4.

In this thesis, we only consider the contention-based channel access, e.g. distributed coordination function (DCF) and enhanced DCF (EDCF) but do not consider the centrally-controlled channel access, e.g. point coordination function (PCF) and hybrid coordination function (HCF).

There are no direct STA-STA traffic flows. The direction that AP sends frames to the stations is called the downlink and the inverse direction is called the uplink. So all traffic flows must be through the AP. Only one physical data rate is used in the saturated WLAN. We do not consider the technologies of the physical layer. But it determines some network parameter values, e.g. SIFS, DIFS and backoff slot time in our analysis.

Many researchers extend the DCF Markov chain model proposed by Bianchi [8] to calculate the throughput and mean delay. Xiao [16] enlarges the original two-dimensional Markov chain to three-dimensional Markov chain. But the analysis of multi-dimensional Markov chain has the high computation complexity. It may not be feasible in real-time to solve a set of non-linear equations. We need a simple and accurate mathematical model to implement to make a better system design, such as deriving optimal call admission control. In our thesis, we propose a simple and more accurate analytical model by the principle of average value approximation.

The rest of this thesis is organized as the follows. Chapter 2 presents the basic knowledge of the 802.11 WLAN about DCF, EDCF, PCF, HCF and RTS/CTS-based contention access mechanism. Chapter 3 presents the related work that has been done before and describes the different analytic method to evaluate the throughput and mean delay. Chapter 4 presents the evaluation of the backoff time between two transmissions in the medium and the channel utilization when the saturated WLAN only supports unidirectional traffic flow. We also compare our analysis with other papers and the results prove our analytic model is better. Chapter 5 presents the evaluation of two cases when the saturated WLAN can support bidirectional traffic flow. The definition of bidirectional traffic flow is also described in Chapter 5. Chapter 6 presents the simulation and numerical results. Chapter 7 presents the conclusion.

Chapter2

Backgrounds

In 1999, the standard about IEEE 802.11 Wireless LANs which specified the specification of Medium Access Control (MAC) layer and Physical layer was defined. Fig.2-1 shows the IEEE 802.11 MAC architecture. The MAC layer of legacy 802.11 has two MAC protocols, Distributed Coordination Function (DCF) and Point Coordination Function (PCF). Then in order to provide more quality of service (QoS), the 802.11e standard also defines two MAC protocols, Enhanced Distributed Channel Access (EDCA) and HCF controlled channel access (HCCA).

There is a diverse set of versions of WLANs in the market, which apply apply different transmission schemes and frequency bands. Fig.2-2 shows the IEEE 802.11 physical architecture. The 802.11b version provides data rate up to 11Mbps, which applies complementary code keying (CCK) and direct sequence spread spectrum (DSSS) as its transmission schemes. It operates in the industrial, scientific, and medical (ISM) band at 2.4GHz. The 802.11a version provides data rate up to 54Mbps, which apply the multicarrier technique orthogonal frequency-division multiplexing (OFDM) as its transmission scheme. It operates in the unlicensed 5GHz band. The 802.11g version applies the same multicarrier transmission scheme as 802.11a, but operates in the 2.4GHz ISM band like 802.11b.

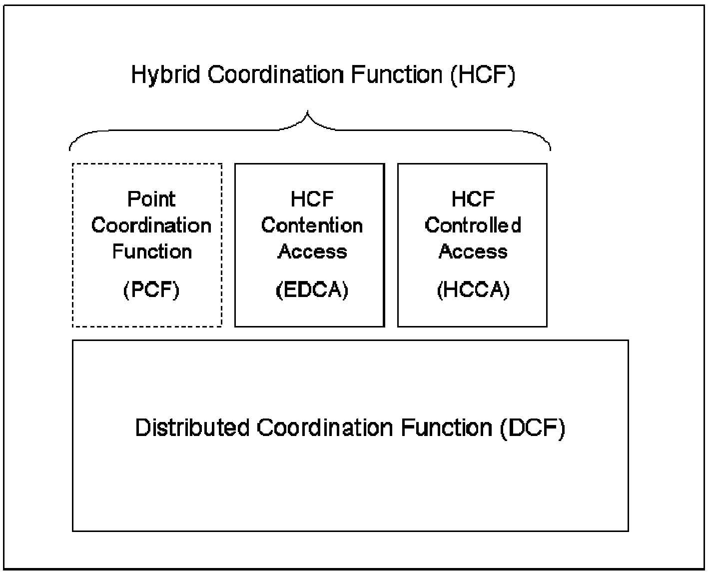

Fig.2-1: IEEE 802.11 MAC architecture

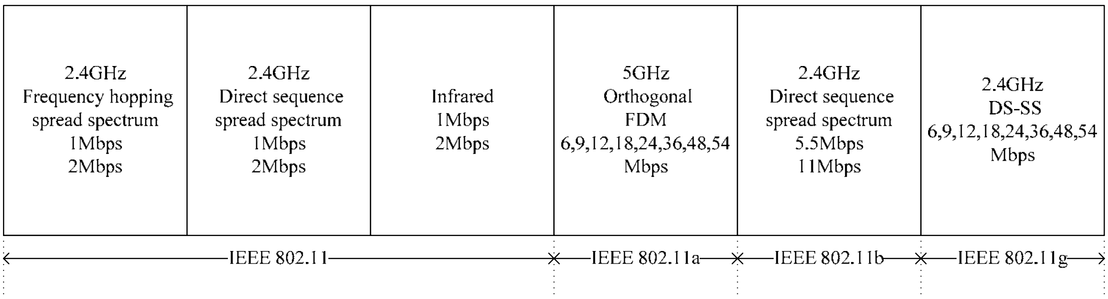

Fig.2-2: IEEE 802.11 physical architecture

2-1 Distributed Coordination Function

The basic access mechanism, called Distributed Coordination Function (DCF) is basically a Carrier Sense Multiple Access with Collision Avoidance mechanism (CSMA/CA). The DCF does not include a Carrier Sense Multiple Access with Collision Detection mechanism (CSMA/CD) because of two main reasons:

(1) Implementing a Collision Detection Mechanism would need the implementation of a Full Duplex radio, capable of transmitting and receiving at once. This approach would increase the price significantly.

(2) On a wireless environment, we can not ensure that all stations can hear each other. But this is the basic assumption of the Collision Detection scheme.

Fig.2-4 shows the basic operation of DCF. In order to reduce the collision probability, the DCF applies a collision avoidance mechanism called backoff procedure. After detecting the channel idle for DCF interframe space (DIFS), stations would still detect the channel for additional random time that is called backoff slots time. Stations would select the number of slots at random out of an interval between 0 and contention window (CW) .As in Ethernet, the backoff time would be selected from a larger range when a transmission fails. Fig.2-3 shows the growth of the contention window when the retransmission numbers increase. Each time the retry counter increases, the CW moves to the next greatest power of two and the size of CW is limited by physical layer.

CW_{min} and CW_{max} are the minimum and maximal contention window sizes respectively, and M is the backoff stage that satisfies $CW_{\max} = 2^M (CW_{\min} + 1) - 1$

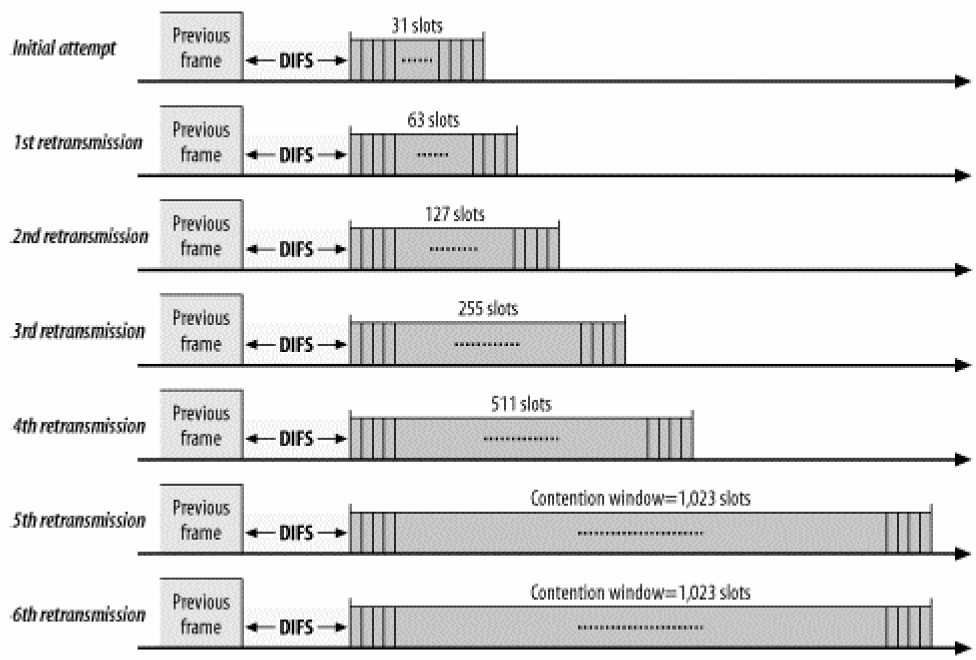

Fig.2-3 Contention Window [1]

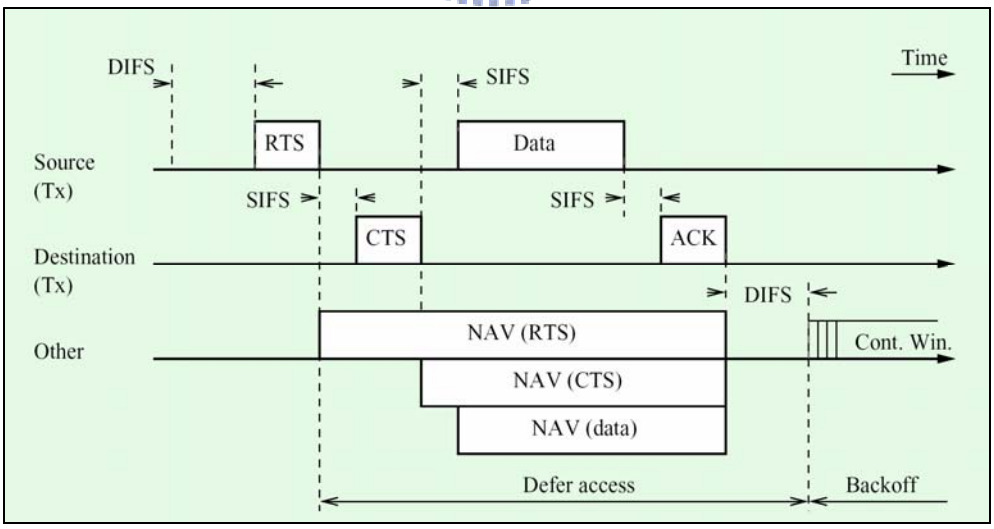

Fig.2-4 Basic operation of DCF (Including RTS/CTS mechanism) [3]

2-2 Point Coordination Function [12]

The IEEE 802.11 standard defines the Point Coordination Function (PCF) in order to support time-bounded services, ex. voice frame and video frame. This priority access to the wireless medium is coordinated by a station called Point Coordinator (PC). Because the PCF may start transmissions after a shorter duration than DIFS but longer than SIFS that is called PCF Interframe Space (PIFS), the PCF has higher priority than the DCF. With PCF, a Contention Free Period (CFP) and a Contention Period (CP) alternate over time. Time is divided into repeated periods, called superframes. A superframe is combined by a CFP and a CP. DCF is used during the CP and PCF is used during the CFP.

A superframe starts with the beacon frame that is a management frame that maintains the synchronization of the local timers in the stations and delivers protocol related parameters. The PC, which is typically collocated with the AP, generates beacon frames at regular beacon frame intervals, thus every station knows when the next beacon will arrive. This time is called target beacon transition time (TBTT) and announced in every beacon frame. See Fig.2-5 for a typical sequence during CFP. Because the PC itself has pending data for this station, it uses a combined data and poll frame by piggybacking the CF-Poll frame on the data frame. If the PC does not receive any response from a polled station after waiting for PIFS, it polls the next station, or ends the CFP. A specific control frame, called CF-End, is transmitted by the PC as the last frame within the CFP to signal the end of the CFP.

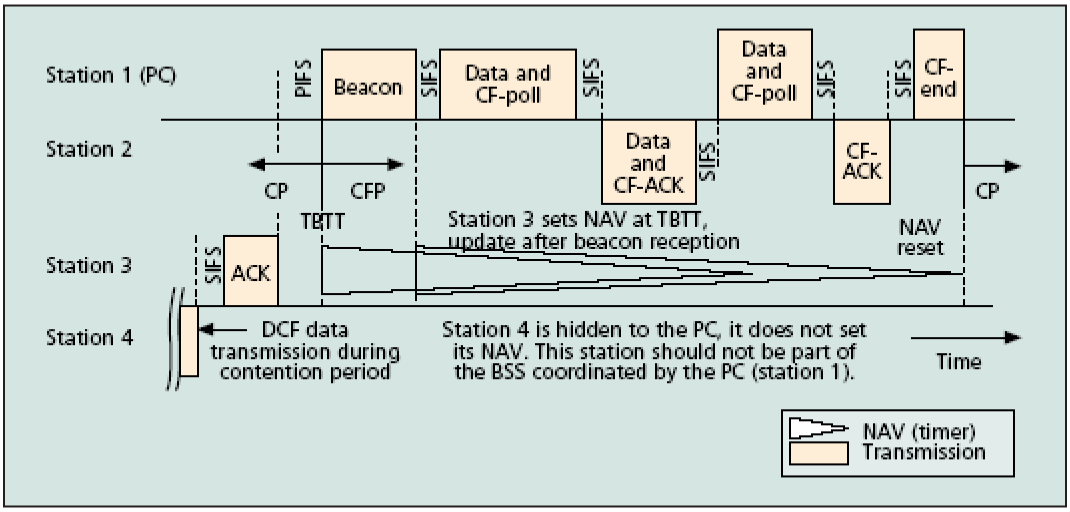

Fig.2-5 An example for the PCF operation [13]

2-3 Enhanced Distributed Coordination Function

IEEE 802.11 Task Group E currently defines enhancements to 802.11 MAC, called 802.11e, which introduces EDCF and HCF. With 802.11e, there may still be two phases of operation within the superframes, i.e., a CP and a CFP, which alternate over time continuously. The EDCF is used in the CP only, while the HCF is used in both phases.

In the CP , each Traffic Category (TC) with the stations contends for a TXOP and independently starts to count down their backoff counter after detecting the channel being idle for an Arbitration Interframe Space (AIFS). The AIFS is at least DIFS. See Fig.2-6 for illustration of the EDCF parameters.

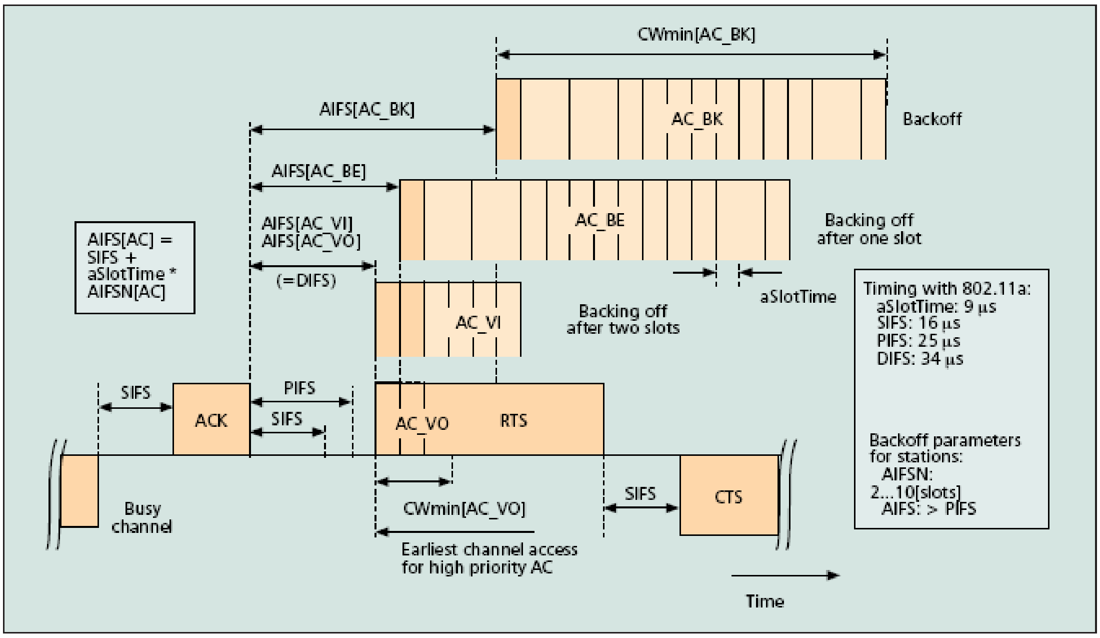

Fig.2-6 Illustration of the EDCF parameters

A single station may implement up to eight transmission queues realized as virtual stations inside a station. If the counters of two or more parallel TCs in a single station reach zero at the same time, a scheduler will avoids the *virtual collision*. The TC with highest priority will get the TXOP and other TCs will increase their CW and choose a value from the interval [0, CW]. There is then still a possibility that the transmitted frame collides at the medium with a frame transmitted by other stations.

Fig.2-7 shows the legacy 802.11 station and 802.11e station with four ACs with one station.

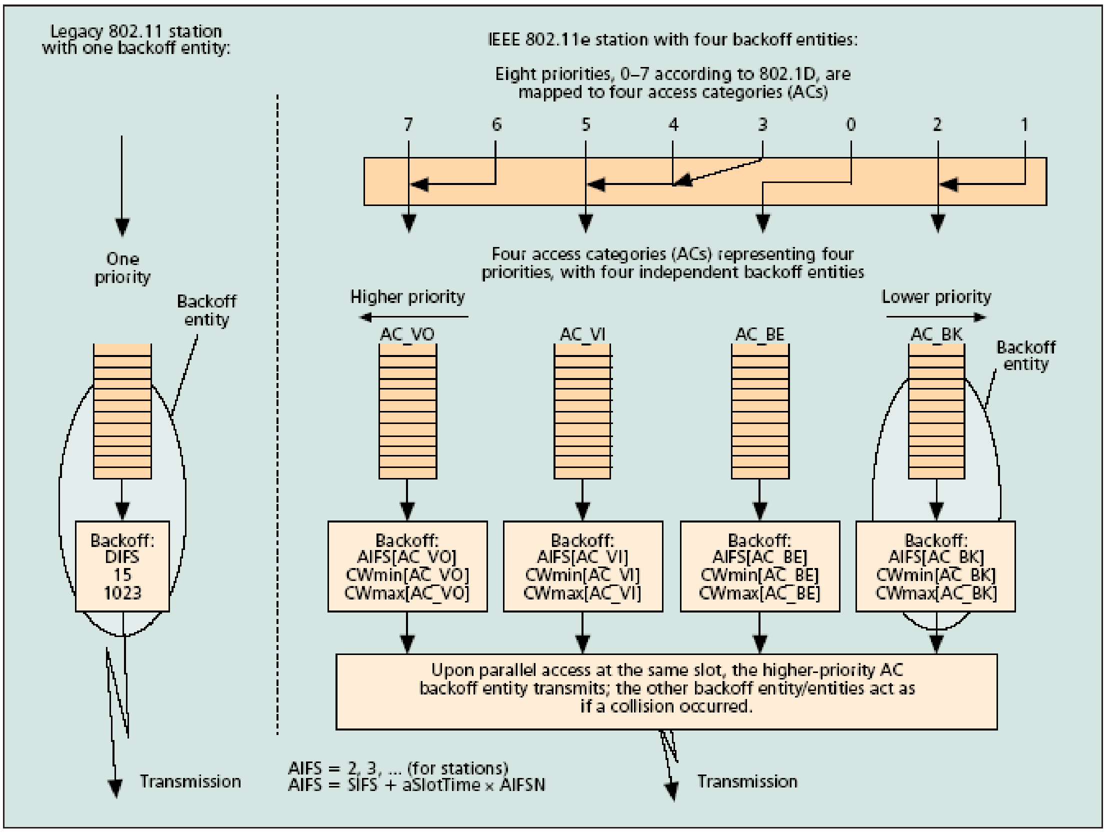

Fig.2-7 the legacy 802.11 station and 802.11e station with four ACs with one station [13]

The EDCA uses AIFS[AC], CW_{min}[AC], and CW_{max}[AC] instead of DIFS, CW_{min}, and CW_{max}, of the DCF. The AIFS[AC] is determined by

$$\text{AIFS[AC]=SIFS + AIFSN[AC]} \times \text{SlotTime}$$

So the EDCA use the different parameter setting to prioritize different services, ex. voice, video, and best effort.

2-4 Hybrid Coordination Function [12] [13]

The HCF extends the EDCF access rules. Only after detecting the channel as being idle for PIFS, the HC may allocate TXOPs to itself to initiate MSDU Deliveries whenever it wants. The QoS CF-Poll from the HC can be sent after a PIFS idle period without any backoff. So the HC can issue the polled TXOPs in the CP using its prioritized medium access.

During the CFP, the starting time and maximum duration of each TXOP is specified by the HC. Stations will not attempt to contend for the channel. Only the HC can grant TXOPs by sending QoS CF-Poll frames. See Fig.2-8 for an example of 802.11e superframe.

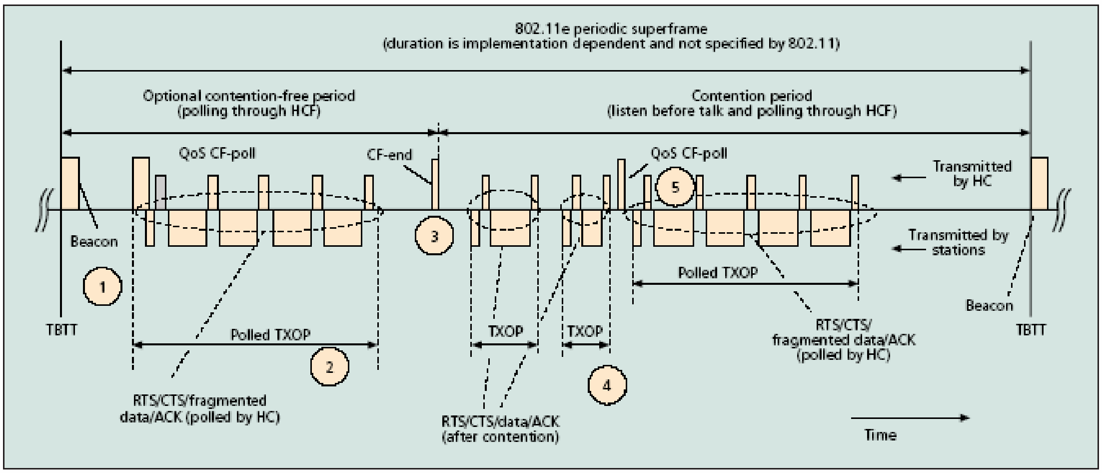

Fig.2-8: An example of 802.11e superframe where the HC grants TXOPs in CFP and CP

2-5 RTS/CTS-based access mechanism

The RTS/CTS-based access mechanism provides positive control over the medium in order to minimize the collisions caused by the hidden stations. Fig.2-9 shows the hidden terminal problem. For example, B is in the transmission range of C, but the others are not. B and D are in the transmission range of C, but A is not. A and C are unaware of each other since their signal do not carry that far. So their frames may collide with each other at B. But unlike an Ethernet, neither A nor C can be aware of the collision. A and C are called “hidden nodes” with respect to each other.

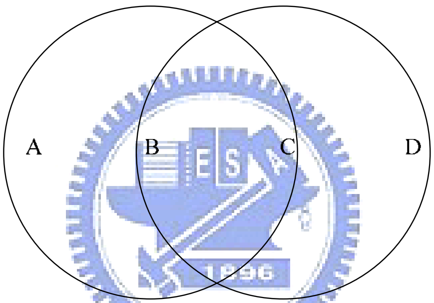

Fig.2-9 hidden node problem

RTS/CTS-based access mechanism can solve the hidden node problem. If A has a frame to B, A will send a RTS frame first. When B receives the RTS frame, B will return a CTS frame that contains a time value that alerts other stations to hold off from accessing the medium. After A receives the CTS frame from B, A will begin to send its data frame. Adding the RTS/CTS access mechanism will increase redundancy. But if the data frame is always large like aggregated frames, the RTS/CTS access mechanism can reduce the collision cost instead. Fig.2-10 shows the RTS/CTS access mode and Basic access mode.

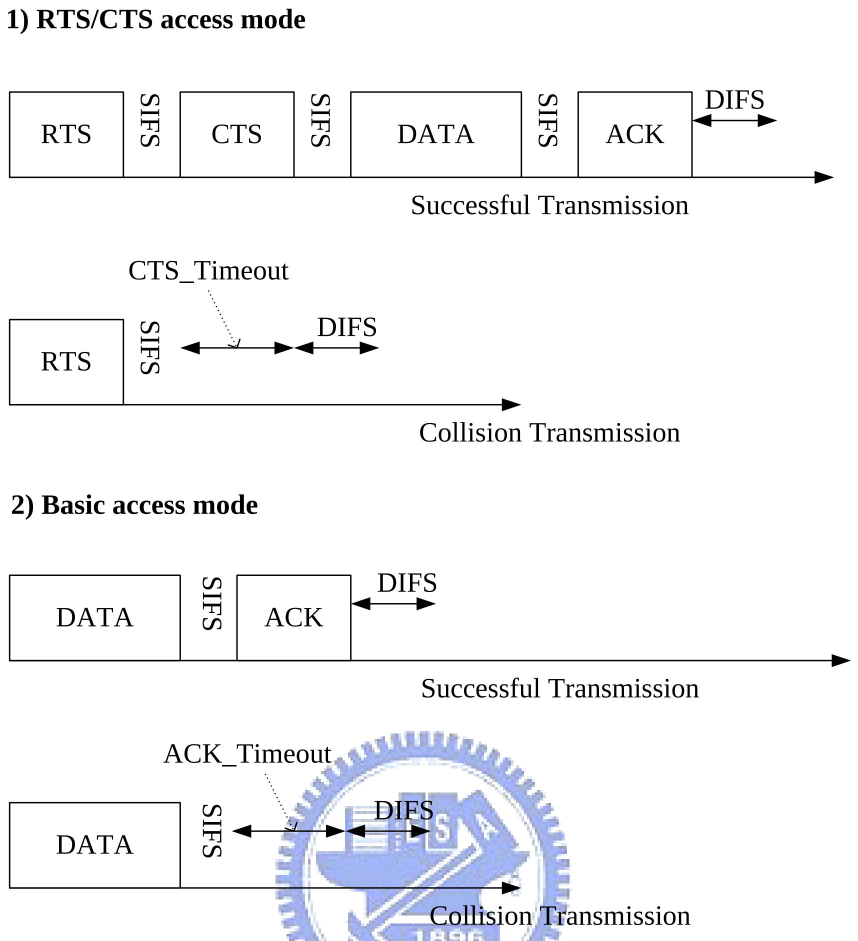

Fig.2-10: RTS/CTS access mode and Basic access mode

Chapter 3

Related Work

With the rapid deployment of the IEEE 802.11 WLANs, there are many studies of contention-based DCF medium access function. In order to reduce the collision probability, the DCF applies a collision avoidance mechanism called backoff procedure. Most of the studies are supposed a saturated WLAN. The saturated throughput or channel utilization are the maximum load that the system can carry in a saturated condition. The definition of a saturated WLAN can be found in the papers [4] [8] [9]. This basic performance figure indicates the limit throughput when the offered traffic load increases.

In the paper [4], it presents an analytic model for computing the capacity of an infrastructure IEEE 802.11 WLAN enhanced with the support of the bidirectional MAC frame aggregation. The analytic model helps us to understand the performance gain of bidirectional aggregation and serve as the foundation for the future aggregation scheduler development.

In the paper [5], this paper uses an analytical model to study the channel capacity when using the basic access (two-way handshaking) method in this analysis. The important contribution in this paper is that it provides closed-form approximations for collision probability p, the maximum throughput S and the limit on the number of stations in a wireless cell. p and S depend on the minimum window size W and the number of stations n only through a gap g = W/(n-1). Consequently, halving W is like doubling n. The maximum contention window size has minimal effect on p and S. The choice of W that maximizes S is proportional to the square root of the packet length. The results of this paper can suggest guidelines on when and how W can be adjusted to suit the measured traffic.

In the paper [14], the author first considers the enhanced DCF access method of IEEE 802.11e. The analytical model can be used to calculate the traffic priority and throughput corresponding to the configuration of multiple DCF contention parameters under the saturated WLAN.

In the paper [15], it provides an analytical model to evaluate the saturation throughput of the IEEE 802.11e EDCA. The analytical model is based on the use of the mean value analysis. It also models accurately the effects of the change of the contention window size and Arbitration Interframe Space (AIFS). This model is applicable to real-time system tuning and on-line admission control algorithms that need a low computation complexity.

In the paper [14], most features of the EDCA such as virtual collision, different arbitration interframe space (AIFS) and different contention window are considered. The throughput and mean delay of differentiated service traffics are analyzed with using the Markov chain model Fig.3-1.

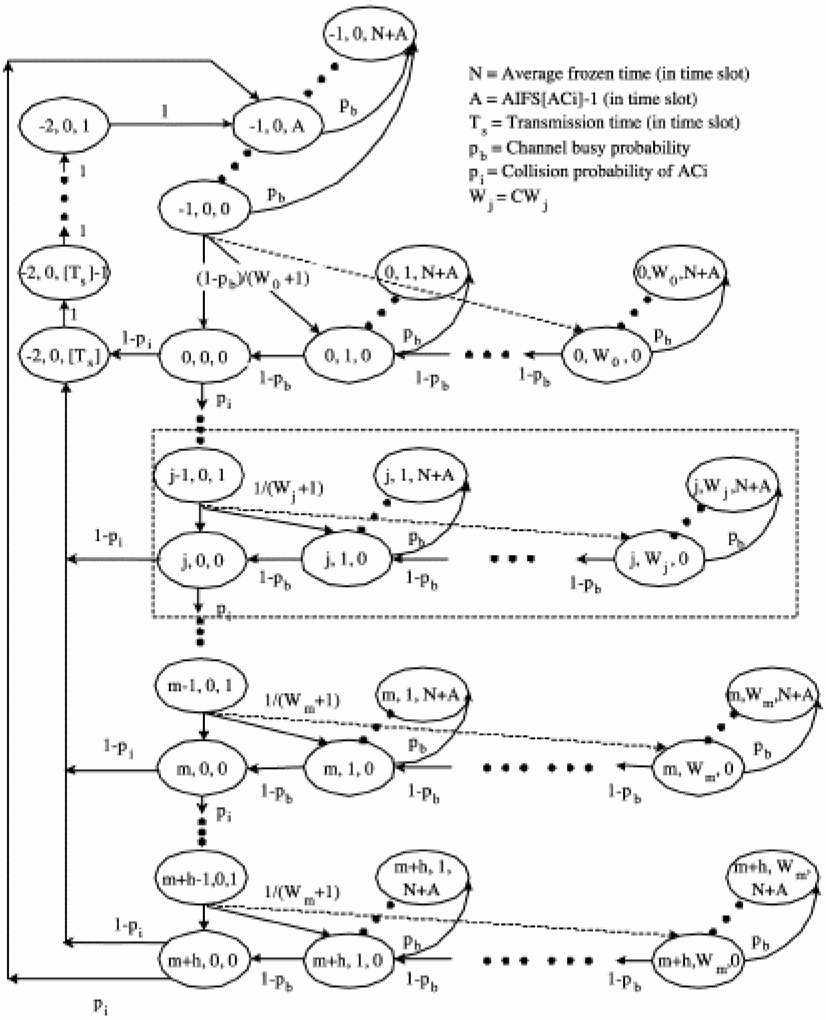

Fig.3-1 Transition diagram of discrete time Markov chain model for one AC per station

Chapter 4

Unidirectional Traffic Flow

To reduce the complexity of analysis, the saturated WLAN [4] [8] [9] is considered in the following sections. A saturated WLAN has the following properties:

(1) All stations and the AP always have a nonempty queue of data frames to transmit.

(2) The traffic distribution to all stations from the AP is uniform. Its meaning is that each station has the same probability to be the destination when the AP wants to send a frame.

(3) The AP always has at least one frame destined to each station waiting in its queue.

Suppose there are N-1 stations and one AP in the saturated WLAN. They have the equal probability $\frac{1}{N}$ to contend for the channel successfully. Fig.4-1 and Fig.4-2 show the scenario of the unidirectional traffic flow. If one station sends an aggregated data frame to the AP. The AP will return the Ack frame to the AP. This is called unidirectional traffic flow. In this thesis, we focus on the case there is at most one aggregated frame as shown in Fig.4-2. Multiple MAC frames carried in a single physical frame is called aggregation or an aggregate. RTS/CTS-based contention access can reduce the collision cost. The channel access in the saturated WLAN is contention-based, e.g. distributed coordination function (DCF) and enhanced DCF (EDCF) as in [10] [11]. Centrally-controlled channel access, e.g. Point Coordination Function (PCF) and HCF Controlled Channel Access (HCF) as in [12] [13] is not considered.

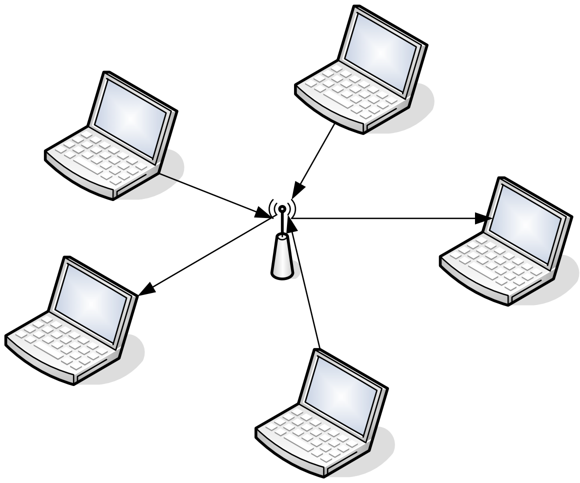

Fig.4-1: WLAN Scenario – Unidirectional Traffic flow

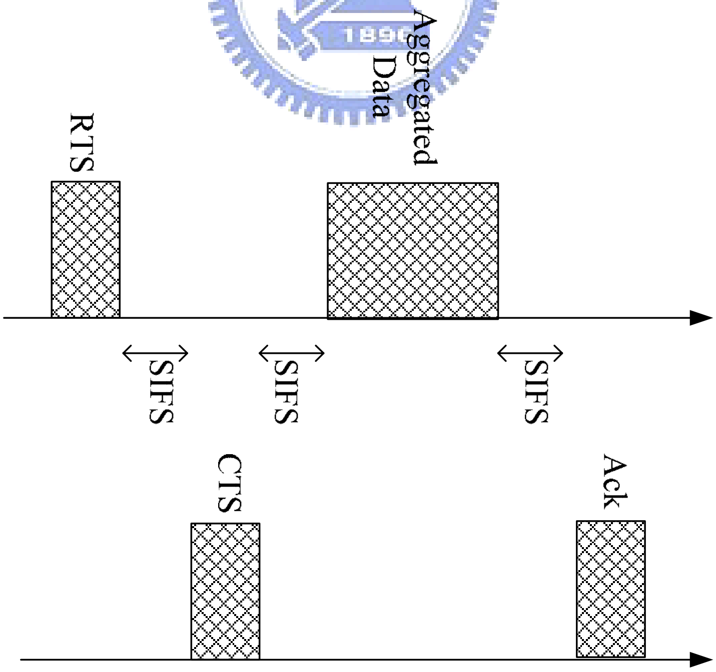

Fig.4-2: Unidirectional Traffic flow with aggregation

4-1 Our Method for Calculating the Channel Utilization

If a collision happens in the channel, the channel will pay $T_{channel\_collision}$ for this collision as shown in Fig. 4-3.

$$T_{channel\_collision} = W_{EmptySlots\_OurAnalysis} \times 20 + T_{RTS} + (T_{CTS} + SIFS + 2\tau) + DIFS \qquad (4.1)$$

$$where \;\; T_{RTS\_timeout} = T_{CTS} + SIFS + 2\tau$$

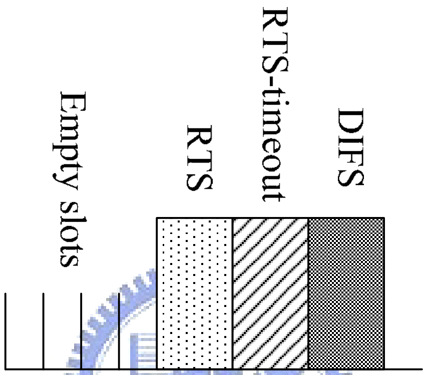

Fig. 4-3 $T_{channel\_collision}$

If a successful transmission happens in the channel, the channel will pay $T_{channel\_success}$ for this successful transmission as shown in Fig. 4-4.

$$T_{channel\_success} = W_{EmptySlots\_OurAnalysis} \times 20 + T_{RTS} + T_{CTS} + T_{phy\_data} + T_{ACK} + 3SIFS + 4\tau + DIFS$$

$$where \;\; T_{phy\_data} = T_{mac\_data} + T_{PLCP\_overhead}$$

(4.2)

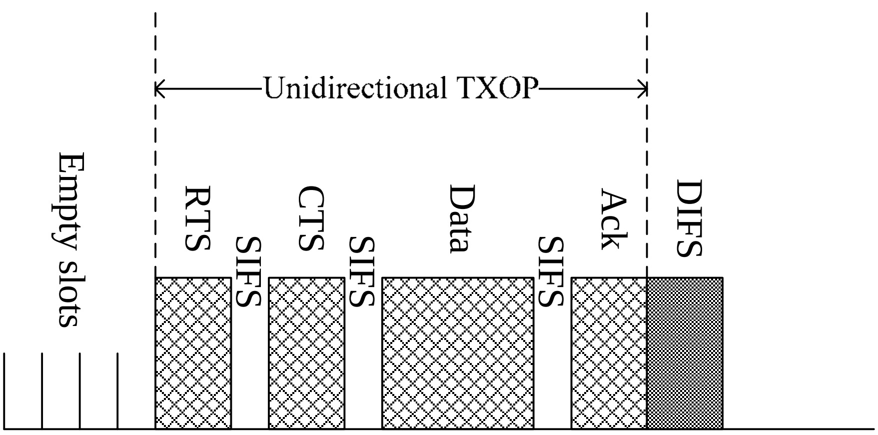

Fig. 4-4 $T_{channel\_success}$ for unidirectional traffic flow

$p_{channel}$ is the probability that a collision happens to the medium. p is the probability that a collision happens to a station. The channel utilization can be represented as below:

$$\mu_{OurAnalysis} = \frac{(1-p_{channel})T_{mac\_data}}{p_{channel}T_{channel\_collision} + (1-p_{channel})T_{channel\_success}} \quad (4.3)$$

$$where \ \ p_{channel} = \frac{\text{Total channel\_collision\_nums}}{\text{Total channel\_transmission\_nums}}$$

T_{mac_data} is the average transmission time for a MAC frame data

$T_{RTS}, T_{CTS}, T_{ACK}, SIFS, DIFS$ and τ are deterministic values. Please reference the table 1 in the chapter 6. Next $p_{channel}$ and $W_{EmptySlots}$ will be calculated as the following sections. From the result in [5] and the equation (4.21), p satisfies

$$p = 1-(1-\frac{1}{W_{uni}})^{N-1} = 1-(1-\frac{1}{[\frac{1-(2p)^M}{2-4p}\times\frac{1-p}{1-p^{K+1}} + \frac{2^{M-1}(p^M - p^{K+1})}{1-p^{K+1}}]W - \frac{1}{2}})^{N-1} \quad (4.4)$$

$$where \ \ p = \frac{\text{total packet\_collision\_nums}}{\text{total packet\_transmission\_nums}}$$

M is the backoff stage that satisfies $CW_{\max} = 2^M CW_{\min} + 2^M - 1$

N is the number of stations (including AP) in the saturated WLAN

In the paper [5], the $r_{success}$ is the rate of successful packet transmissions and the r_{xmit} is the rate of packet transmissions (including packet collisions). Then the average number of transmission per packet is $\frac{r_{xmit}}{r_{success}}$.

$$\frac{1}{1-p} = \frac{r_{xmit}}{r_{success}} \quad (4.5)$$

Suppose one channel_collision_num contains two packet_collision_num . So the rate of channel collisions $r_{collision}$ is given by

$$r_{xmit} - r_{success} = 2r_{collision} \tag{4.6}$$

T_{cycle} is the time between two payload transmissions – and consist of successful and collided transmissions.

$$\frac{1}{T_{cycle}} = r_{success} + r_{collision} \tag{4.7}$$

From equations (4.4)-(4.6), we can get a conclusion

$$r_{success} = \frac{2(1-p)}{2-p}\frac{1}{T_{cycle}} \tag{4.8}$$

$$r_{xmit} = \frac{2}{2-p}\frac{1}{T_{cycle}} \tag{4.9}$$

$$r_{collision} = \frac{p}{2-p}\frac{1}{T_{cycle}} \tag{4.10}$$

So the $p_{channel}$ can be calculated as below

$$p_{channel} = \frac{r_{collision}}{r_{success} + r_{collision}} = \frac{p}{2-p} \tag{4.11}$$

Next we will explain how to estimate the average value ($W_{EmptySlots}$) of the backoff time between two transmissions in the medium in the chapter 4-2.

4-2 The Proposed Method of Paper [4] for Calculating the Channel Utilization

In this paper [4], the channel utilization can be expressed as below:

$$\mu_{paper1} = \frac{m_v}{t_v} \tag{4.12}$$

Where t_v is the average period between two successful transmissions, which is defined in [9]. It is also called *virtual transmission time* and m_v is the average data frame size (MAC data frame size in this thesis) successfully transmitted during t_v. Fig.4-5 shows the concept of a virtual transmission time.

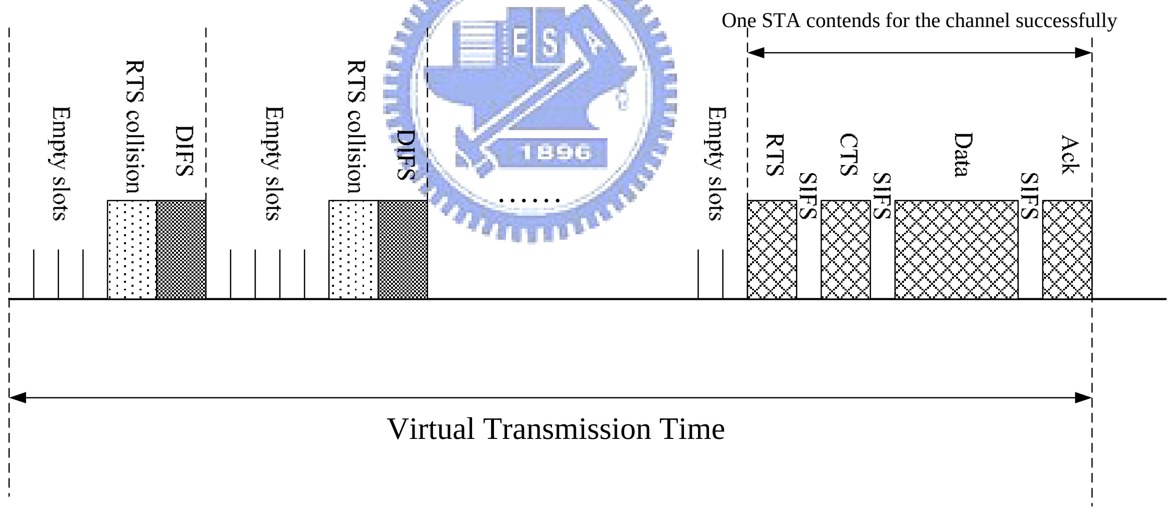

Fig.4-5 a virtual transmission time

So t_v can be expressed as below:

$$\begin{aligned} \mathrm{t}_V &= E[\sum_{i=1}^{N_c}(T_{Idle\_P_i} + T_{Coll_i} + DIFS)] + E[T_{Idle\_P_{N_c+1}}] + T_{TXOP} \\ &= \sum_{i=1}^{N_c+1} E[T_{Idle\_P_i}] + N_c(T_{Coll_i} + DIFS) + T_{TXOP} \end{aligned} \tag{4.13}$$

T_{TXOP} is the time duration for a TXOP in a virtual transmission time.

$$T_{TXOP} = T_{RTS} + T_{CTS} + T_{phy\_data} + T_{ACK} + 3\times SIFS + 4\times\tau \tag{4.14}$$

where T_{phy_data} is the average transmission time for a physical data frame

T_{Coll_i} is the duration of the i-th collision in a virtual transmission time.

$$T_{Coll_i} = T_{RTS} + T_{RTS-timeout} \text{ where } T_{RTS-timeout} = \tau + SIFS + T_{CTS} + \tau \tag{4.15}$$

From the result of [4],

$$\begin{aligned} t_v &= \frac{W_{uni\_1}}{N} \times 20 + \frac{p}{1-p}(T_{RTS} + T_{RTS-timeout} + DIFS) \\ &\quad + T_{RTS} + T_{CTS} + T_{phy\_data} + T_{ACK} + 3 \times SIFS + 4 \times \tau \\ &= \frac{W_{uni\_1}}{N} \times 20 + \frac{T_{RTS} + T_{CTS}}{1-p} + \frac{3-2p}{1-p} SIFS + \frac{4-2p}{1-p}\tau + \frac{p}{1-p} DIFS + T_{phy\_data} + T_{ACK} \end{aligned} \tag{4.16}$$

And

$$\begin{aligned} \mu_{paper1} &= \frac{m_v}{t_v} \\ &= \frac{T_{mac\_data}}{\frac{W_{uni\_1}}{N} \times 20 + \frac{T_{RTS} + T_{CTS}}{1-p} + \frac{3-2p}{1-p} SIFS + \frac{4-2p}{1-p}\tau + \frac{p}{1-p} DIFS + T_{phy\_data} + T_{ACK}} \end{aligned}$$

$$where \quad T_{mac\_data} = \frac{8 \times mac\_data}{11} \times 10^{-6} \tag{4.17}$$

4-3 How to Calculate $W_{EmptySlots}$

A station would select the number of slots at random out of an interval between 0 and contention window (CW). The backoff time would be selected from a larger range when a transmission fails. Each time the retry counter increases, the CW moves to the next greatest power of two and the size of CW is like the equation as below:

$$CW = 2^m \; CW_{\min} + 2^m - 1 \tag{4.18}$$

where $CW_{\min}$ is the minimum contention window

Define W_x be the average number of backoff slots experienced by a packet until it is transmitted successfully or discarded in the saturated WLAN with unidirectional traffic flow

.

$$\begin{aligned}
W_x &= (1-p)\frac{CW_{\min}}{2} + p(1-p)\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2}\right\} \\
&+ p^2(1-p)\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2} + \frac{2^2 CW_{\min}+2^2-1}{2}\right\} \\
&+ \cdots + p^M(1-p)\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2} + \cdots + \frac{2^M CW_{\min}+2^M-1}{2}\right\} \\
&+ p^{M+1}(1-p)\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2} + \cdots + \frac{2^M CW_{\min}+2^M-1}{2} + \frac{2^M CW_{\min}+2^M-1}{2}\right\} \\
&+ \cdots + p^K(1-p)\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2} + \cdots + \underbrace{\frac{2^M CW_{\min}+2^M-1}{2} + \cdots + \frac{2^M CW_{\min}+2^M-1}{2}}_{K-M+1}\right\} \\
&+ p^{K+1}\left\{\frac{CW_{\min}}{2} + \frac{2CW_{\min}+2-1}{2} + \cdots + \underbrace{\frac{2^M CW_{\min}+2^M-1}{2} + \cdots + \frac{2^M CW_{\min}+2^M-1}{2}}_{K-M+1}\right\}
\end{aligned}$$

$$= \frac{CW_{\min}}{2} + p\frac{2CW_{\min}+2-1}{2} + \cdots + p^{M-1}\frac{2^{M-1}CW_{\min}+2^{M-1}-1}{2} + (p^M + p^{M+1} + \cdots + p^K)\frac{2^M CW_{\min}+2^M-1}{2}$$

$$= \frac{CW_{\min}}{2} + p\frac{2CW_{\min}+2-1}{2} + \cdots + p^{M-1}\frac{2^{M-1}CW_{\min}+2^{M-1}-1}{2} + \frac{p^M - p^{K+1}}{1-p}\frac{2^M CW_{\min}+2^M-1}{2}, let\ W = CW_{\min}+1$$

$$= \frac{W-1}{2} + p\frac{2W-1}{2} + \cdots + p^{M-1}\frac{2^{M-1}W-1}{2} + \frac{p^M - p^{K+1}}{1-p}\frac{2^M W-1}{2}$$

$$= \left[\frac{1-(2p)^M}{2-4p} + \frac{2^{M-1}(p^M - p^{K+1})}{1-p}\right]\times[CW_{\min}+1] - \frac{1-p^{K+1}}{2-2p} \qquad (4.19)$$

where K is the maximal retransmission number

Define x be the average transmissions experienced by a packet until it is transmitted successfully or discarded in the saturated WLAN with unidirectional traffic flow.

$$\begin{aligned} x &= (1-p)\times 1 + p(1-p)\times 2 + p^2(1-p)\times 3 + \ldots + p^K(1-p)\times(K+1) + p^{K+1}(K+1) \\ &= 1 + p + p^2 + \ldots + p^K \\ &= \frac{1-p^{K+1}}{1-p} \end{aligned} \qquad (4.20)$$

Let $W_{uni} = \frac{W_x}{x}$, we get the average time that a station makes a transmission.

$$W_{uni} = \frac{W_x}{x} = [\frac{1-(2p)^M}{2-4p}\times\frac{1-p}{1-p^{K+1}} + \frac{2^{M-1}(p^M - p^{K+1})}{1-p^{K+1}}]W - \frac{1}{2} \qquad (4.21)$$

If p^{K+1} is close to zero, then W_{uni} will approach to the equation as below. This equation is the same as the papers [4] [5] [6].

$$W_{uni\_1} = \lim_{p^{K+1}\to 0} W_{uni} = \frac{1-p-p(2p)^M}{1-2p}\frac{CW_{\min}+1}{2} - \frac{1}{2} \qquad (4.22)$$

Next we will discuss three types of $W_{EmptySlots}$ as below:

4-3-1 The Proposed Method of Paper [4]

In the long term, the AP and each STA will get a fair share of channel accesses for transmitting their frames, and in particular, the average period of virtual transmission time for the AP and each STA is $N \times t_v$. In this paper [4], it concludes a conclusion that the total empty slots in a virtual transmission time as below:

$$\sum_{i=1}^{N_c+1} E[Idle\_p_i] = \frac{W_{uni\_1}}{N} \tag{4.23}$$

Random variable N_c is the number of collisions in a virtual transmission time and it is a geometrical distribution. So its mean can be calculated as below:

$$P\{N_c = i\} = p^i(1-p) \tag{4.24}$$

$$E[N_c] = \sum_{i=0}^{+\infty} i \times P\{N_c = i\} = \sum_{i=0}^{+\infty} i \times p^i(1-p) = \frac{p}{1-p} \tag{4.25}$$

The backoff slots between two transmissions in the medium can be calculated from the equation as below:

$$\mathrm{W}_{\mathrm{EmptySlots\_paper1}} = \frac{W_{uni\_1}}{N} \times (1-p) \tag{4.26}$$

4-3-2 The Proposed Method of Paper [5] [6]

At a saturated WLAN, most transmission are preceded by a minimum backoff of $CW_{\min}$; when N stations uniformly choose a time in $CW_{\min}$, the separation between choices has mean $\frac{CW_{\min}}{N+1}$. In particular, the station that picks the earliest slots breaks the channel silence after the time $\frac{CW_{\min}}{N+1}$. So we can express the equation as below:

$$W_{EmptySlots\_paper2} = \frac{CW_{\min}}{N+1} \tag{4.27}$$

4-3-3 Our Analytic Method

Every station will make a transmission for every W_{uni}th in average. After the DIFS time interval, some station must count down its backoff counter from W_{uni}. Please see the Fig.4-6. Suppose other stations will count down their backoff counter form r.v. $\{X_1, X_2, \cdots, X_{N-1}\}$. We model $\{X_1, X_2, \cdots, X_{N-1}\}$ by Uniform distribution from $[0, W_{uni}]$. Let Y = min$\{X_1, X_2, \cdots, X_{N-1}\}$ and Y means the backoff slots between two transmissions in the medium. Its cumulative distribution function, $F_Y(y)$, can be calculated as below:

$$
\begin{aligned}
F_Y(y) &= P(Y \le y) \\
&= 1 - P(Y > y) \\
&= 1 - P\left(\min\{X_1, X_2, \cdots, X_{N-1}\} > y\right) \\
&= 1 - P\left(X_1 > y, X_2 > y, \cdots, X_{N-1} > y\right) \\
&= 1 - P(X_1 > y)^{N-1} \\
&= 1 - \left(1 - \frac{y}{W_{uni}}\right)^{N-1}
\end{aligned}
\tag{4.28}
$$

Its probability density function, $f_Y(y)$, can be calculated as below:

$$
\begin{aligned}
f_Y(y) &= \frac{dF_Y(y)}{dy} \\
&= \frac{1 - \left(1 - \frac{y}{W_{uni}}\right)^{N-1}}{dy} \\
&= \frac{N-1}{W_{uni}}\left(1 - \frac{y}{W_{uni}}\right)^{N-2}
\end{aligned}
\tag{4.29}
$$

The mean of Y can be calculated as below:

$$
\begin{aligned}
E[Y] &= \int_0^{W_{uni}} y \cdot f_Y(y)\, dy \\
&= \frac{N\text{-}1}{W_{uni}} \cdot \int_0^{W_{uni}} y \cdot \left(1 - \frac{y}{W_{uni}}\right)^{N-2} dy \\
&= \frac{N\text{-}1}{W_{uni}} \cdot \left\{ y \cdot \frac{-W_{uni}}{N-1} \left(1 - \frac{y}{W_{uni}}\right)^{N-1} \right\}_0^{W_{uni}} - \frac{N\text{-}1}{W_{uni}} \cdot \int_0^{W_{uni}} \frac{-W_{uni}}{N-1} \left(1 - \frac{y}{W_{uni}}\right)^{N-1} dy \\
&= \int_0^{W_{uni}} \left(1 - \frac{y}{W_{uni}}\right)^{N-1} dy \\
&= \left\{ \frac{\text{-}W_{uni}}{N} \left(1 - \frac{y}{W_{uni}}\right)^{N} \right\}_0^{W_{uni}} \\
&= \frac{W_{uni}}{N} \qquad (4.30)
\end{aligned}
$$

Therefore, the backoff slots between two transmissions in the medium as below:

$$W_{EmptySlots\_OurAnalysis} = \frac{W_{uni}}{N} \qquad (4.31)$$

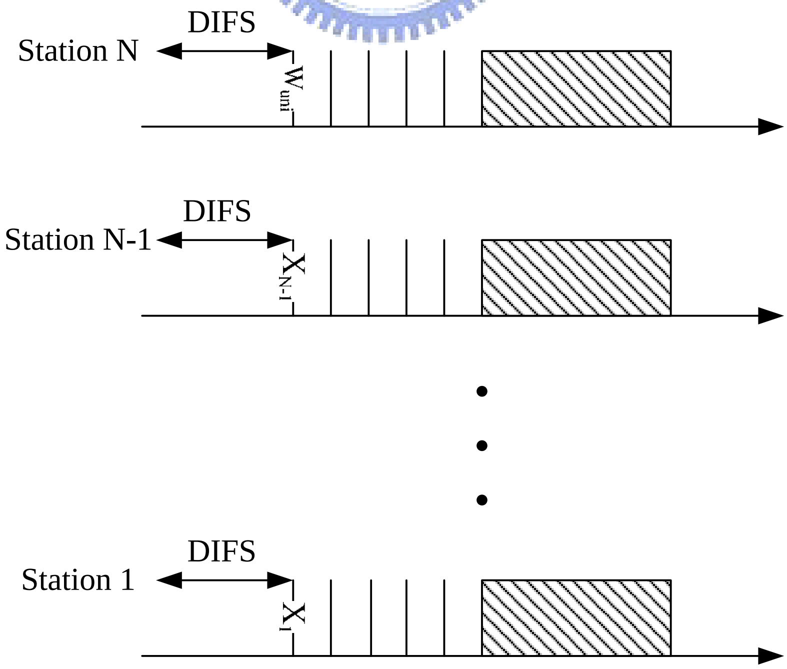

Fig.4-6 virtual backoff procedure

Chapter 5

Bidirectional Traffic Flow

Fig.5-1 and Fig.5-2 show the scenarios of the bidirectional traffic flow. In the scenario of the unidirectional traffic flow, if a frame is transmitted successfully, the backoff counter will be reset. But in the scenario of the bidirectional traffic flow, when a frame is transmitted successfully, the backoff counter may not be reset. The key point is if the frame in the front of the buffer or not. There are examples as below.

(1) One station sends an aggregated data frame to the AP. The AP will return the Ack+AggregatedData frame to the station. If the AggregatedData frame is at the head of buffer in the AP, the backoff counter of AP will be reset by the piggyback. If not, the counter will not be reset.

(2) The AP sends an aggregated data frame to some station. The station will return the Ack+AggregatedData frame to the AP. The backoff counter of the station must be reset by the piggyback.

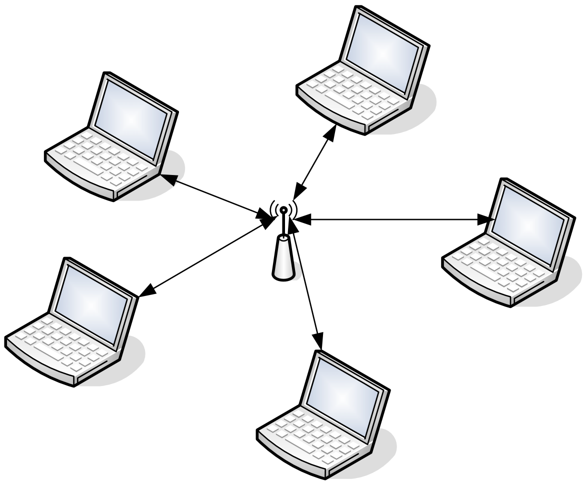

Fig.5-1: WLAN Scenario – Bidirectional traffic flow

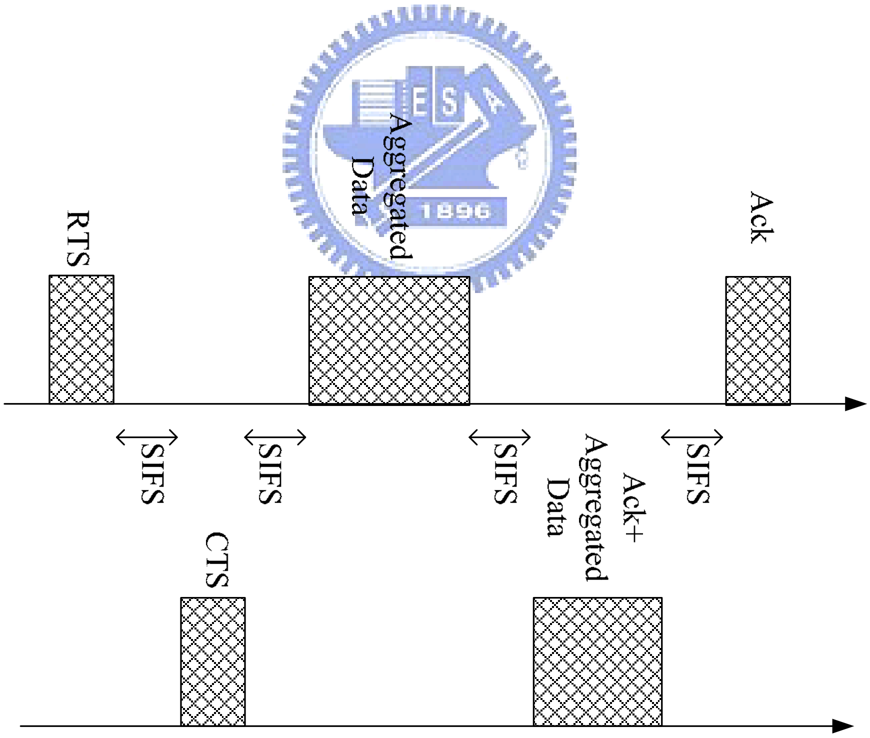

Fig.5-2: Bidirectional traffic flow with aggregation

5-1 Our Method for Calculating the Channel Utilization

If a collision happens in the channel, the channel will pay $T_{channel\_collision}$ for this collision. The $T_{channel\_collision}$ is the same as the Fig. 4-3.

If a successful transmission happens in the channel, the channel will pay $T_{channel\_success}$ for this successful transmission as shown in Fig. 5-3

$$T_{channel\_success} = W_{EmptySlots\_OurAnalysis} \times 20 + T_{RTS} + T_{CTS} + T_{phy\_up\_data} + T_{phy\_down\_data} + T_{ACK} + 4SIFS + 5\tau + DIFS$$

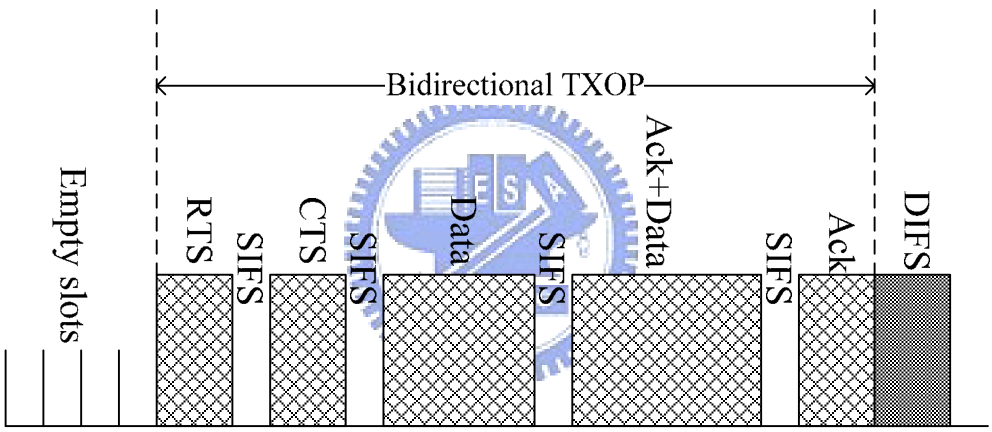

Fig.5-3 Successful transmission state for bidirectional traffic flow

$p_{channel}$ is the probability that a collision happens to the medium. p is the probability that a collision happens to a station. The channel utilization can be represented as below:

$$\mu_{OurAnalysis} = \frac{(1 - p_{channel})(T_{mac\_up\_data} + T_{mac\_down\_data})}{p_{channel} T_{channel\_collision} + (1 - p_{channel}) T_{channel\_success}}$$

$$where \quad T_{mac\_up\_data} + T_{mac\_down\_data} = \frac{8 \times 2 \times mac\_data}{11} \times 10^{-6} \qquad (5.1)$$

T_{RTS} , T_{CTS} , T_{ACK} , $SIFS$, $DIFS$ and τ are deterministic values. Please reference the table 1 in the chapter 6. Next $p_{channel}$ and $W_{EmptySlots}$ will be calculated as the following sections. From the result in [5] and the equation (5.17), p satisfies

$$p = 1 - (1 - \frac{1}{W_{bi}})^{N-1} \tag{5.2}$$

Similar to the evaluation of (4.11), $p_{channel}$ is

$$p_{channel} = \frac{r_{collision}}{r_{success} + r_{collision}} = \frac{p}{2 - p} \tag{5.3}$$

5-2 The Proposed Method of Paper [4] for Calculating the Channel Utilization

Fig.5-4 shows a virtual transmission time. The evaluation is the same as the chapter 4.

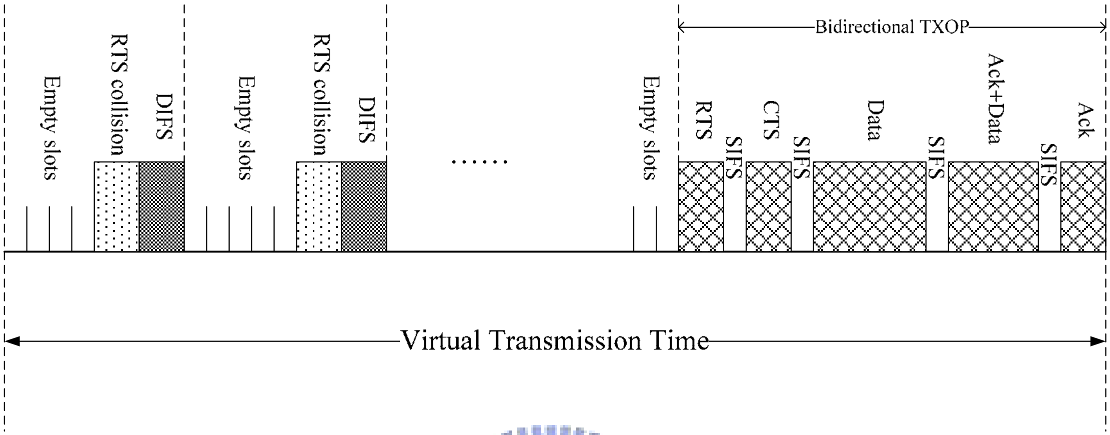

Fig.5-4 A virtual transmission time

So t_v can be expressed as below:

$$
\begin{aligned}
t_V &= E[\sum_{i=1}^{N_c}(T_{Idle\_P_i} + T_{Coll_i} + DIFS)] + E[T_{Idle\_P_{N_c+1}}] + T_{TXOP} \\
&= \sum_{i=1}^{N_c+1} E[T_{Idle\_P_i}] + N_c(T_{Coll_i} + DIFS) + T_{TXOP}
\end{aligned}
\quad (5.4)
$$

T_{TXOP} is the time duration for a TXOP in a virtual transmission time.

$$T_{TXOP} = T_{RTS} + T_{CTS} + T_{up} + T_{down} + T_{ACK} + 4 \times SIFS + 5 \times \tau \quad (5.5)$$

T_{Coll_i} is the duration of the i-th collision in a virtual transmission time.

$$T_{Coll_i} = T_{RTS} + T_{RTS-timeout} \text{ where } T_{RTS-timeout} = \tau + SIFS + T_{CTS} + \tau \quad (5.6)$$

From the result of [4], t_v can be expressed as below:

$$
\begin{aligned}
t_v &= \frac{W_{bidirectional}}{N-1} \times 20 + \frac{p}{1-p}(T_{RTS} + T_{RTS-timeout} + DIFS) \\
&\quad + T_{RTS} + T_{CTS} + T_{up} + T_{down} + T_{ACK} + 4 \times SIFS + 5 \times \tau \\
&where\ p\ satisfies\ \ p\frac{1-p-p(2p)^M}{1-2p} = \frac{2}{CW_{\min}}\left(1+\frac{2}{3}N\right)\frac{N-1}{N}\ \ in\ the\ [4]\ [5]
\end{aligned}
\tag{5.7}
$$

where T_{up} and T_{down} are the average transmission time for a physical data frame in the uplink and downlink directions respectively

$$
m_v = T_{mac\_up} + T_{mac\_down} \tag{5.8}
$$

where T_{mac_up} and T_{mac_down} are the average transmission time for a MAC data frame in the uplink and downlink directions respectively

The utilization in [4] can be expressed as:

$$
\begin{aligned}
\mu_{paper1} &= \frac{m_v}{t_v} \\
&= \frac{T_{mac\_up} + T_{mac\_down}}{T_{up} + T_{down} + \frac{W_{bidirectional}}{N-1} \times 20 + \frac{T_{RTS} + T_{CTS}}{1-p} + \frac{5-3p}{1-p}\tau + \frac{4-3p}{1-p}SIFS + \frac{p}{1-p}DIFS + T_{Ack}} \\
&where\ \mathrm{T}_{\mathrm{mac\_up}} + T_{mac\_down} = \frac{8 \times 2 \times mac\_data}{11} \times 10^{-6}
\end{aligned}
\tag{5.9}
$$

5-3 How to Calculate $W_{EmptySlots}$

5-3-1 Our Analytic Method

Suppose there are N stations (including the AP) in the saturated WLAN. They have the equal probability $\frac{1}{N}$ to contend for the channel successfully. Fig.5-5shows a possible transmission pair in the saturated WLAN that supports bidirectional traffic flow. (AP,STA_i) represents that the AP contends for the channel successfully to send a frame to STA_i and STA_i will return a Ack+AggregatedData frame to the AP. So the backoff counter of the STA_i can be reset by the piggyback. (STA_{N-1},AP) represents that STA_{N-1} contends for the channel successfully to send a frame to the AP and the AP will return a Ack+AggregatedData frame to the STA_{N-1}. If this frame is in the head of the buffer, the backoff counter of the AP can be reset by the piggyback..

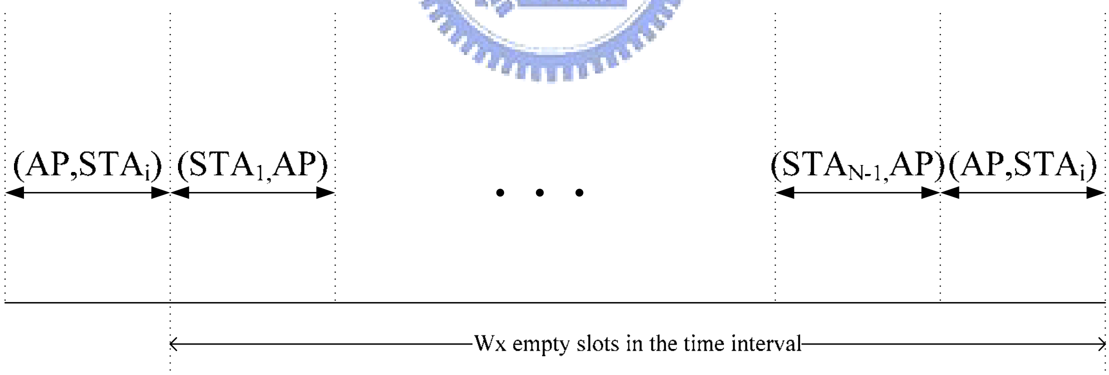

Fig.5-5 A possible transmission pair in the saturated WLAN that supports bidirectional traffic flow for the AP

Next we will extend the concept from the unidirectional traffic flow to the bidirectional traffic flow. W_x is the average number of backoff slots experienced by a packet until it is transmitted successfully or discarded in the saturated WLAN with unidirectional traffic flow. From the equation (4.19) and Fig. 5-5, we approximate the time interval that the AP contends for the channel successfully by W_x. Next we will discuss the average time interval after which the backoff counter of the AP can be reset through the piggyback.

(1) If the reset happens in the pair (STA_1,AP), the time interval is $\frac{1}{N}W_x$

(2) If the reset happens in the pair (STA_2,AP), the time interval is $\frac{2}{N}W_x$

⋮

(N-1) If the reset happens in the pair (STA_{N-1},AP), the time interval is $\frac{N-1}{N}W_x$

So the average time interval after which the backoff counter of the AP is reset by the piggyback is $\frac{W_x}{2}$. If the backoff counter of the AP is not reset by the piggyback, the average time interval after which the backoff counter is reset is W_x.

Case Ⅰ: The backoff counter can be reset by the piggyback. The average time interval is $\frac{W_x}{2}$.

The probability of this case is:

$$\frac{N-1}{N}\times\frac{1}{N-1}=\frac{1}{N} \tag{5.10}$$

Let y_1 be the average number of transmission tries for the AP during $\frac{W_x}{2}$ and we can get the average time between two successive transmissions. Let's recall the calculation x (4.20), if p is small, it will be smaller than 1.5. Since y_1 is smaller than x, we approximate y_1 by 1.

Case Ⅱ: The backoff counter can not be reset by the piggyback. The average time interval is $\mathrm{W_x}$.

The probability of this case is:

$$1-\frac{1}{N}=\frac{N-1}{N} \tag{5.11}$$

The number of transmissions in the time interval $\mathrm{W_x}$ is y_2

$$y_2=\frac{1-p^{K+1}}{1-p} \tag{5.12}$$

We suppose that the AP in a saturated WLAN that supports bidirectional traffic flow will make a transmission for every W_{bi_AP}th slot in average: We estimate W_{bi_AP} by

$$W_{bi\_AP}=\frac{1}{N}\left(\frac{\frac{W_x}{2}}{y_1}\right)+\frac{N-1}{N}\left(\frac{W_x}{y_2}\right) \tag{5.13}$$

Next we will discuss the case that a station will make a transmission for every W_{bi_STA}th slot in average. As shown in Fig.5-6, we approximate the time interval that $\mathrm{STA_1}$ contends for the channel successfully by $\mathrm{W_x}$.

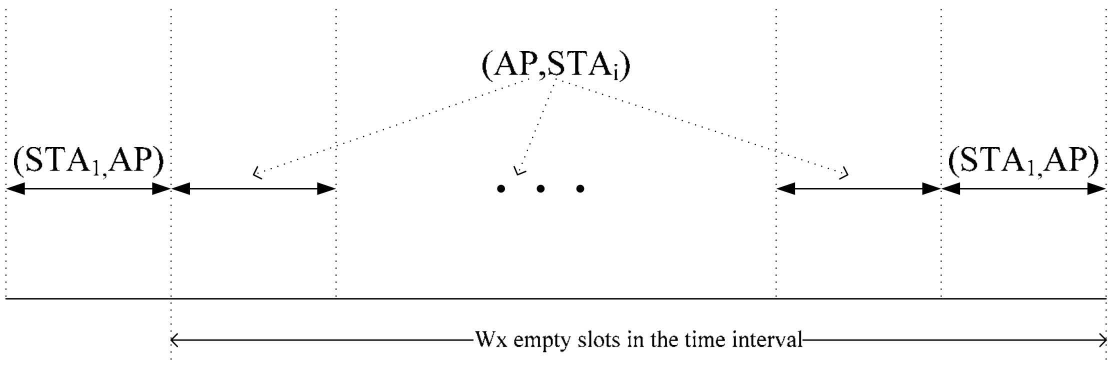

Fig.5-6 A possible transmission pair in the saturated WLAN that supports bidirectional traffic flow for $\mathrm{STA_1}$

Let $(\mathrm{AP},\mathrm{STA}_i)$ denote the event that AP contends for the channel successfully and STA_i sends a frame to AP by the piggyback. For an example, the pair $\{(\mathrm{AP},\mathrm{STA}_i)|\ i = 1\}$ indicates the backoff counter of STA_1 is reset by the piggyback. The average time interval after which the backoff counter of STA_1 is reset by the piggyback is $\frac{\mathrm{W}_x}{2}$. Otherwise, the average time interval after which the backoff counter of STA_1 is reset is W_x.

Case Ⅰ: The backoff counter is reset by the piggyback. The average time interval is $\frac{\mathrm{W}_x}{2}$.

The probability of this case is:

$$\frac{1}{N}\times\frac{1}{N-1} \tag{5.14}$$

Case Ⅱ: The backoff counter is not reset by the piggyback. The average time interval is W_x.

The probability of this case is:

$$1-\frac{1}{N(N-1)}=\frac{N^2-N-1}{N(N-1)} \tag{5.15}$$

We suppose that one station in a saturated WLAN that supports bidirectional traffic flow will make a transmission for every W_{bi_STA}th slot in average, we estimate W_{bi_STA} by

$$W_{bi\_STA}=\frac{1}{N(N-1)}\left(\frac{\frac{W_x}{2}}{y_1}\right)+\frac{N^2-N-1}{N^2-N}\left(\frac{W_x}{y_2}\right) \tag{5.16}$$

So the AP or stations in a saturated WLAN that supports bidirectional traffic flow will make a transmission for every W_{bi}th slot in average:

$$W_{bi} = \frac{W_{bi\_AP} + (N-1)W_{bi\_STA}}{N} \tag{5.17}$$

Similar to the analysis in chapter 4, $W_{EmptySlots\_OurAnalysis}$ can be expressed as:

$$W_{EmptySlots\_OurAnalysis} = \frac{W_{bi}}{N} \tag{5.18}$$

5-3-2 The Proposed Method of Paper [4]

There are two possible ways to piggyback it

(1) Each station always has at least one frame to the AP. If the AP contends for the channel successfully and send a frame to a particular station (with probability $\frac{1}{N-1}$). The frame in the front of the buffer in the particular station can be piggybacked to the AP.

(2) The AP always has at least one frame to every station. If one station contends for the channel successfully (with probability $\frac{1}{N-1}$) and send a frame to the AP. The frame in the AP to the station can be piggybacked to the station.

In these two cases, the backoff counter is half of $W_{bidirectional}$. Therefore, the actual average backoff counter for a station or AP satisfies:

$$W_{bidirectional} = \frac{N-2}{N-1} W_{unidirectional} + \frac{1}{N-1} \times \frac{1}{2} \times W_{bidirectional} \tag{5.19}$$

$$W_{bidirectional} = \frac{2N-4}{2N-3} \times \left\{ \frac{1-p-p(2p)^M}{1-2p} \frac{CW_{\min}+1}{2} - \frac{1}{2} \right\} \tag{5.20}$$

The average period of virtual transmission time for the AP and each STA is (N-1) × t_v. In this paper, it gets a conclusion that the total empty slots in a virtual transmission time as below:

$$\sum_{i=1}^{N_c+1} E[Idle\_p_i] = \frac{W_{bidirectional}}{N-1} \tag{5.21}$$

Random variable N_c is the number of collisions in a virtual transmission time and it is a geometrical distribution. So its mean can be calculated as below:

$$P\{N_c = i\} = p^i (1-p) \tag{5.22}$$

$$E[N_c] = \sum_{i=0}^{+\infty} i \times P\{N_c = i\} = \sum_{i=0}^{+\infty} i \times p^i (1-p) = \frac{p}{1-p} \tag{5.23}$$

The backoff slots between two transmissions in the medium in the saturated WLAN that support bidirectional traffic flow can be calculated from the equation as below:

$$\begin{aligned} W_{EmptySlots\_paper1} &= \sum_{i=1}^{N_c+1} E[Idle\_p_i] \times (1-p) \\ &= \frac{W_{bidirectional}}{N-1} \times (1-p) \end{aligned} \tag{5.24}$$

Chapter 6

Simulate and Numerical Results

Table 1 lists the parameters of the 802.11 WLAN shared by the simulate environment and analytic equation.

Parameter	Value
τ	1 μ sec
SIFS	10 μ sec
DIFS	50 μ sec
Slot time	20 μ sec
PLCP header bit rate	1Mbps
PLCP overhead	192 μ sec
Basic bit rate	5.5Mbps
Data bit rate	11Mbps
T_{RTS}	PLCP overhead $+\frac{20\times 8}{5500000}=221\ \mu\text{sec}$
T_{CTS}	PLCP overhead $+\frac{14\times 8}{6000000}=212\ \mu\text{sec}$
T_{ACK}	PLCP overhead $+\frac{14\times 8}{6000000}=212\ \mu\text{sec}$

Table 6-1 Input parameters and values

From (4.11) (4.4) (5.2), we can give the values of $CW_{\min}$ and M to calculate the analytic collision probabilities p by bisection method.

Equation (4.11) → $p\dfrac{1-p-p(2p)^M}{1-2p}=\dfrac{2}{CW_{\min}}\left(1+\dfrac{2}{3}N\right)\dfrac{N-1}{N}$

Equation (4.4) → $p=1-(1-\dfrac{1}{W_{uni}})^{N-1}$

Equation (5.2) → $p=1-(1-\dfrac{1}{W_{bi}})^{N-1}$

N	p (4.11)	p (4.4)	p (uni_simu)	p (5.2)	p (bi_simu)
2	0.069635	0.060255	0.058818	0.076564	0.063079
5	0.17607	0.18443	0.18725	0.18847	0.18733
10	0.27885	0.29721	0.29686	0.29809	0.31553
15	0.3434	0.36411	0.36818	0.36441	0.38798
20	0.3894	0.41147	0.42304	0.41159	0.43765
25	0.4249	0.4483	0.4644	0.44835	0.47694

Table 6-2 Simulate and analytic values for p with $CW_{\min}$ =31 and $M=K$ =5

Next we will divide this chapter to four parts:

(1) The backoff time between two transmissions in the medium in the saturated WLAN that only supports unidirectional traffic flow.

(2) The backoff time between two transmissions in the medium in the saturated WLAN that supports bidirectional traffic flow.

(3) The channel utilization in the saturated WLAN that only supports unidirectional traffic flow.

(4) The channel utilization in the saturated WLAN that supports bidirectional traffic flow.

6-1 The backoff time between two transmissions in the medium in the saturated WLAN that only supports unidirectional traffic flow.

Equation (4.26) -> $W_{EmptySlots\_paper1} = \dfrac{W_{uni\_1}}{N} \times (1-p)$

Equation (4.27) -> $W_{EmptySlots\_paper2} = \dfrac{CW_{\min}}{N+1}$

Equation (4.31) -> $W_{EmptySlots\_OurAnalysis} = \dfrac{W_{uni}}{N}$

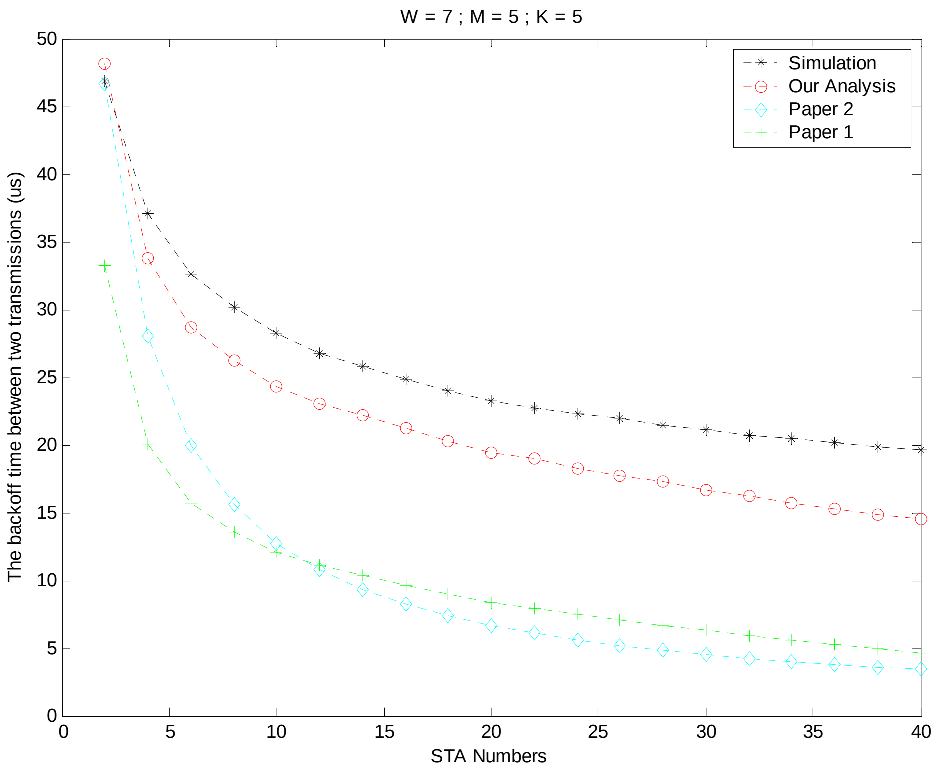

Fig.6-1 $W_{EmptySlots}$ for unidirectional traffic flow (W=7; M=5; K=5)

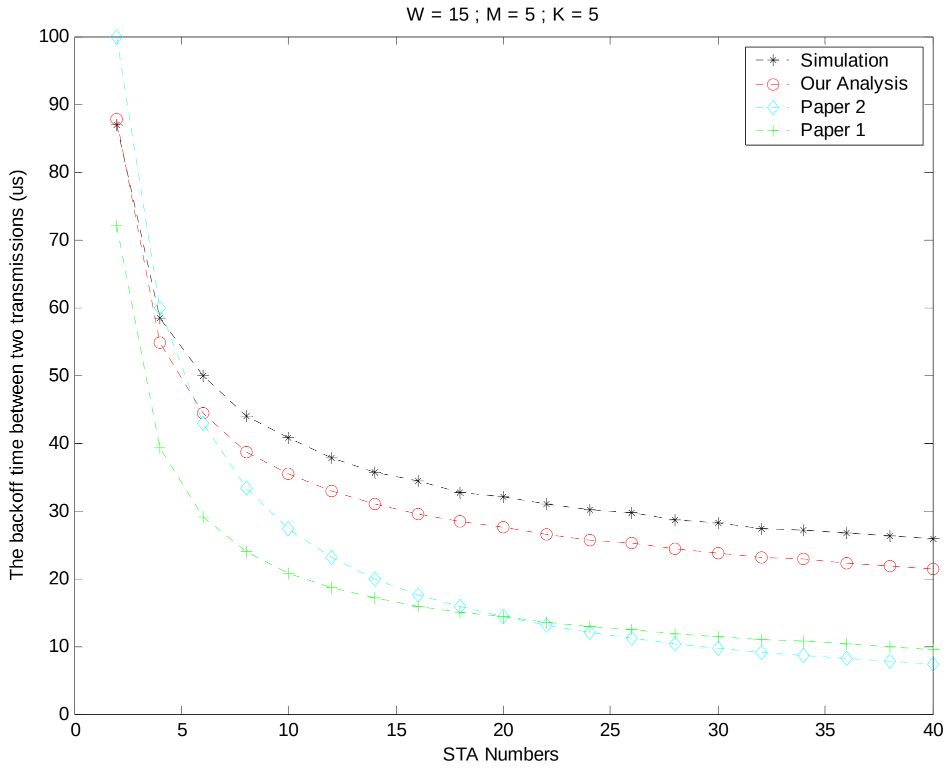

Fig.6-2 $W_{EmptySlots}$ for unidirectional traffic flow (W=15; M=5; K=5)

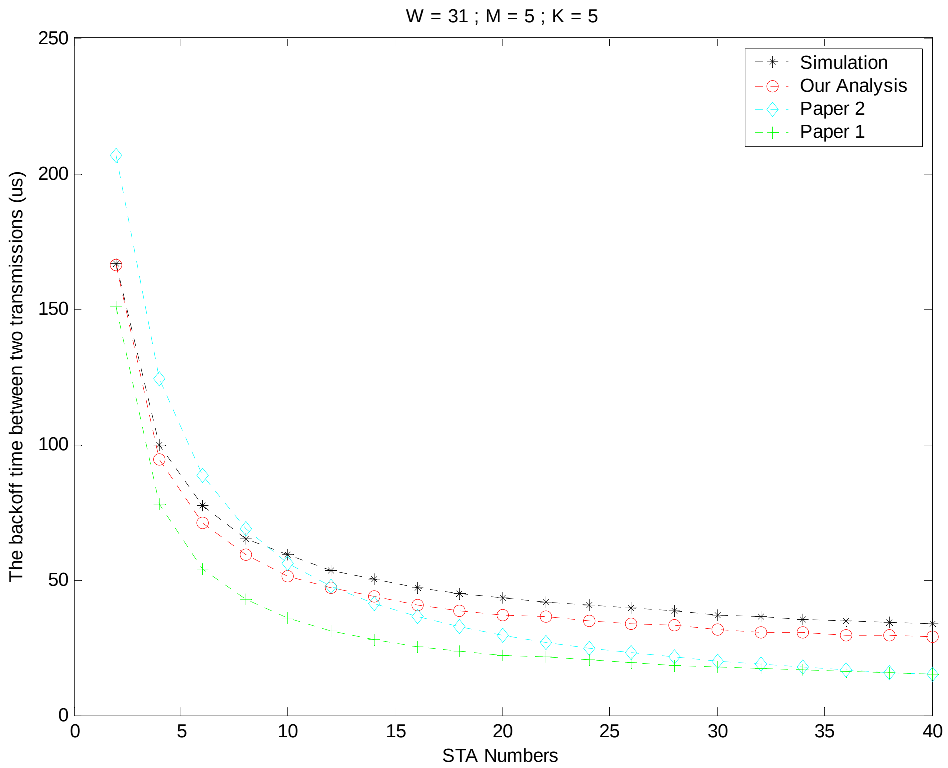

Fig.6-3 $W_{EmptySlots}$ for unidirectional traffic flow (W=31; M=5; K=5)

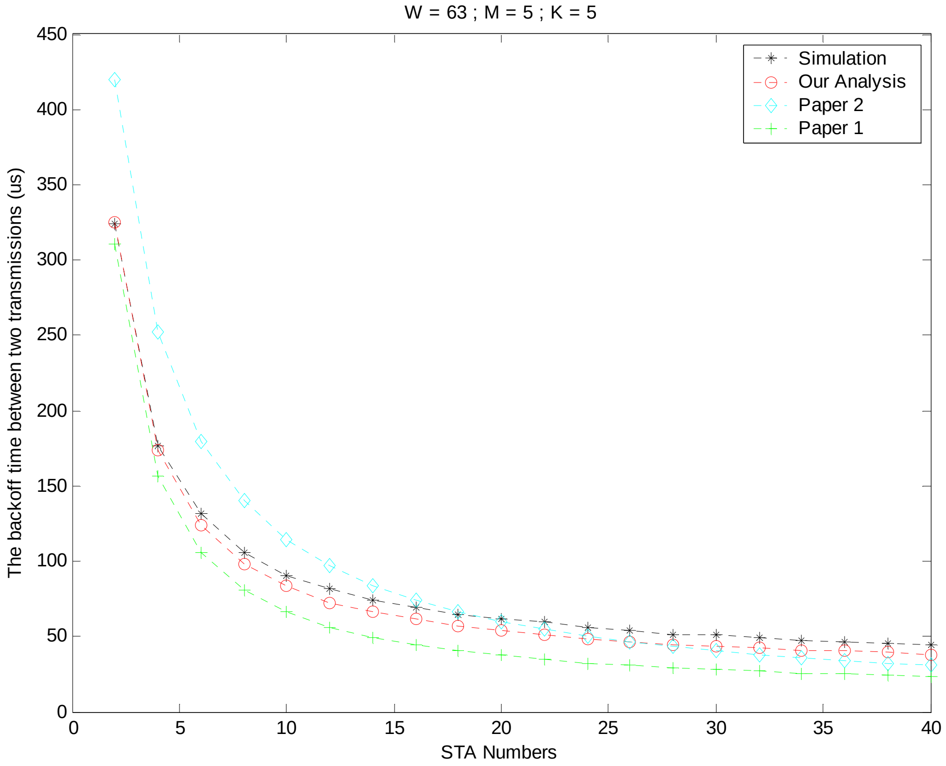

Fig.6-4 $W_{EmptySlots}$ for unidirectional traffic flow (W=63; M=5; K=5)

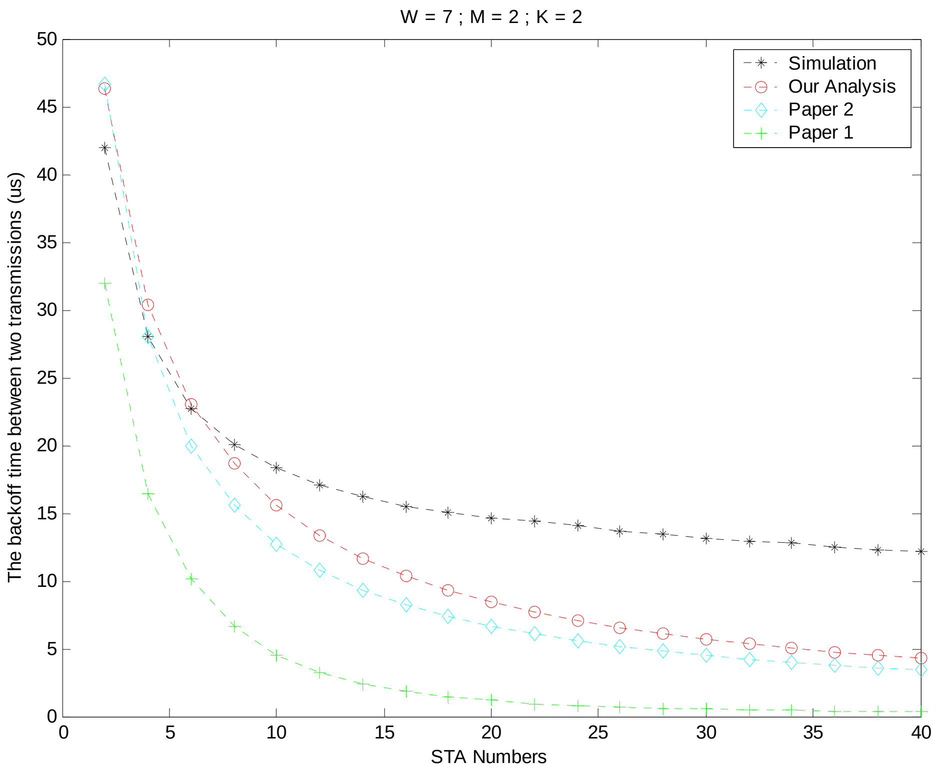

Fig.6-5 $W_{EmptySlots}$ for unidirectional traffic flow (W=7; M=2; K=2)

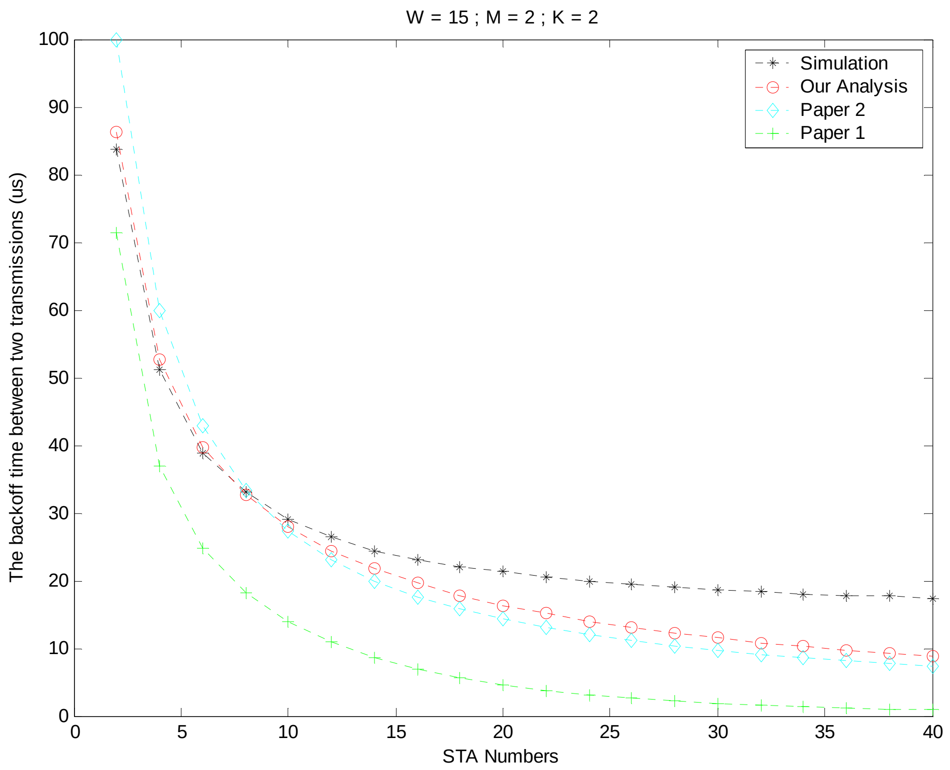

Fig.6-6 $W_{EmptySlots}$ for unidirectional traffic flow (W=15; M=2; K=2)

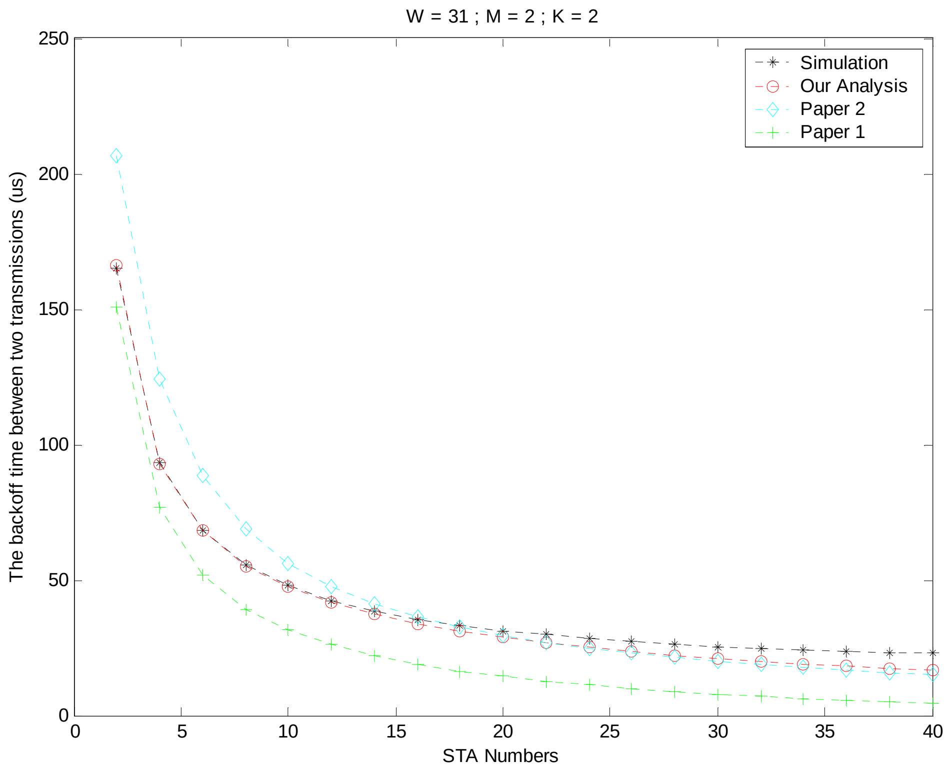

Fig.6-7 $W_{EmptySlots}$ for unidirectional traffic flow (W=31; M=2; K=2)

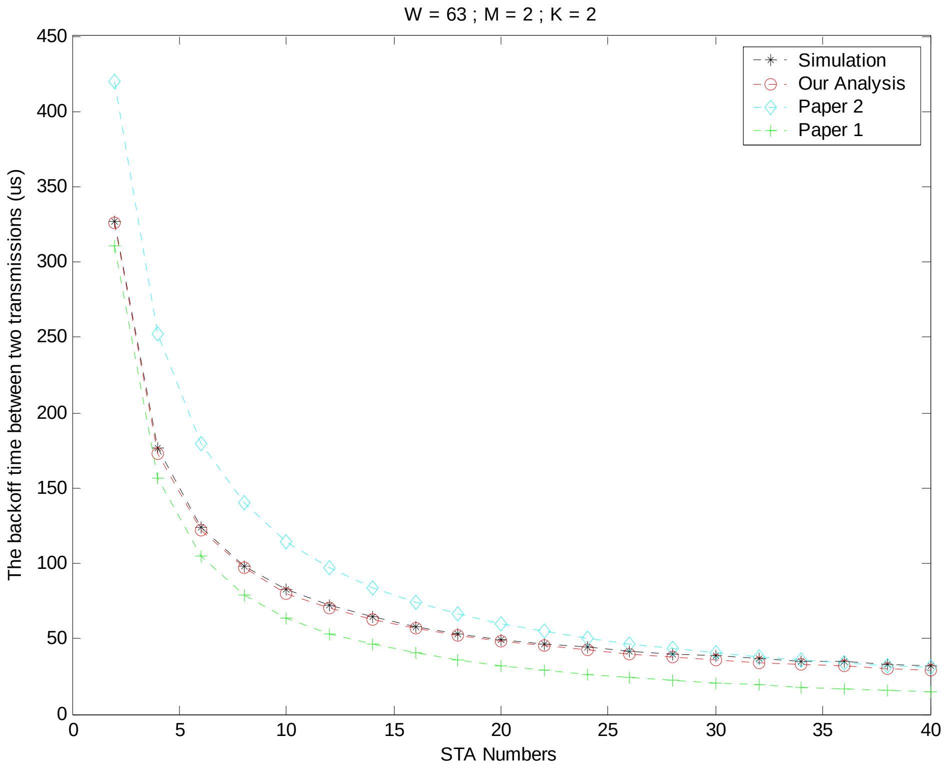

Fig.6-8 $W_{EmptySlots}$ for unidirectional traffic flow (W=63; M=2; K=2)

6-2 The backoff time between two transmissions in the medium in the saturated WLAN that only supports bidirectional traffic flow.

Equation (5.18) -> $W_{EmptySlots\_OurAnalysis} = \dfrac{W_{bi}}{N}$

Equation (5.24) -> $W_{EmptySlots\_paper1} = \dfrac{W_{bidirectional}}{N-1} \times (1-p)$

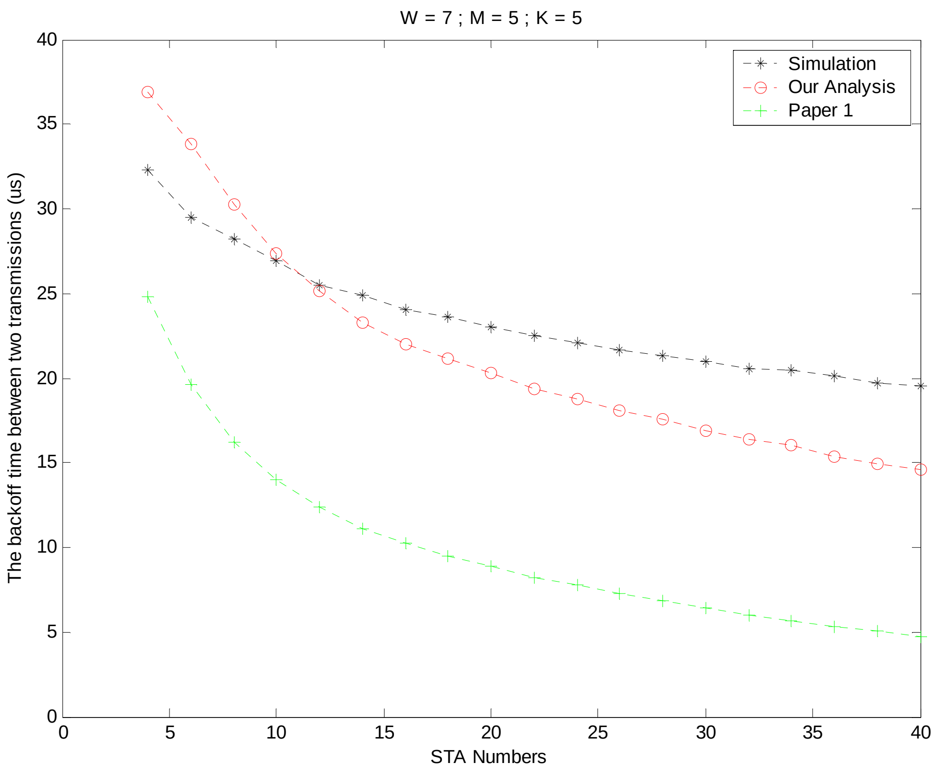

Fig.6-9 $W_{EmptySlots}$ for bidirectional traffic flow (W=7; M=5; K=5)

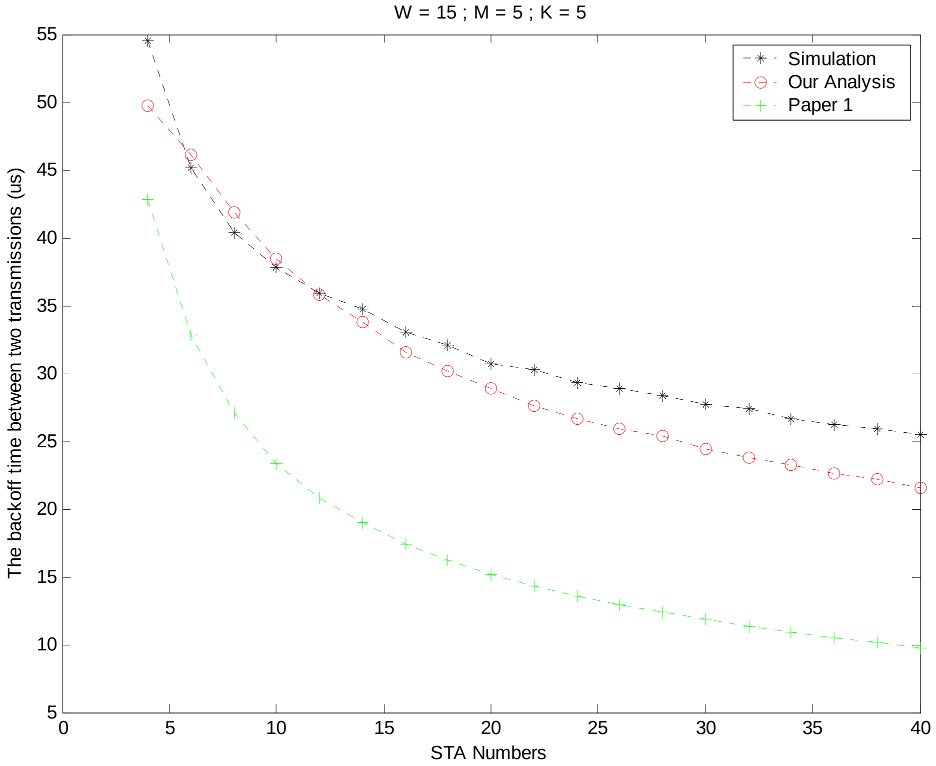

Fig.6-10 $W_{EmptySlots}$ for bidirectional traffic flow (W=15; M=5; K=5)

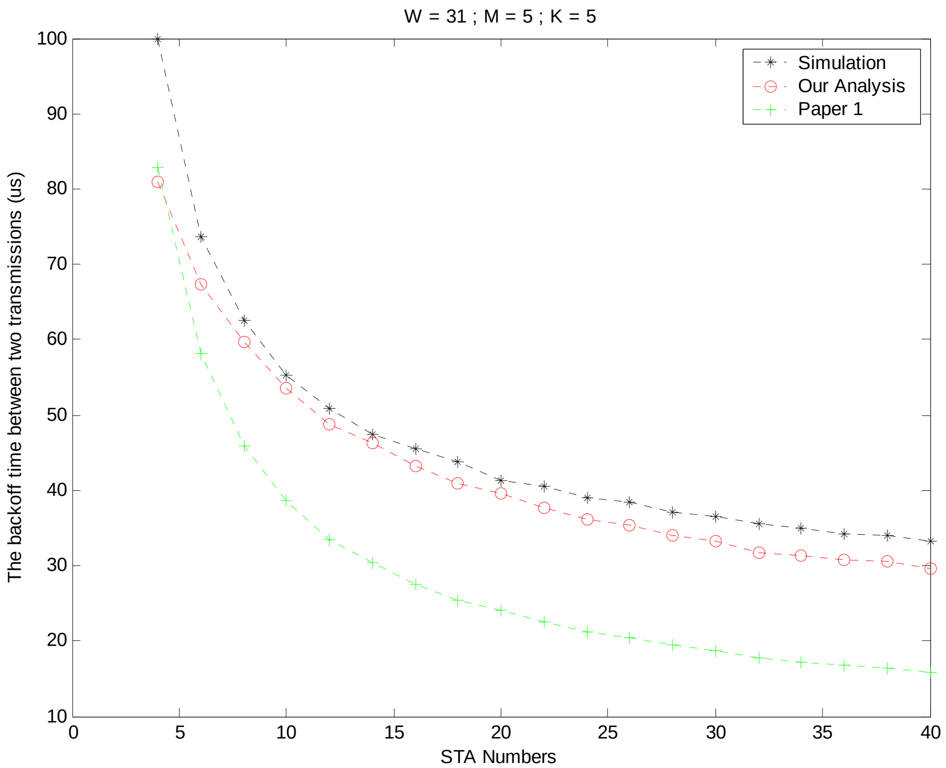

Fig.6-11 $W_{EmptySlots}$ for bidirectional traffic flow (W=31; M=5; K=5)

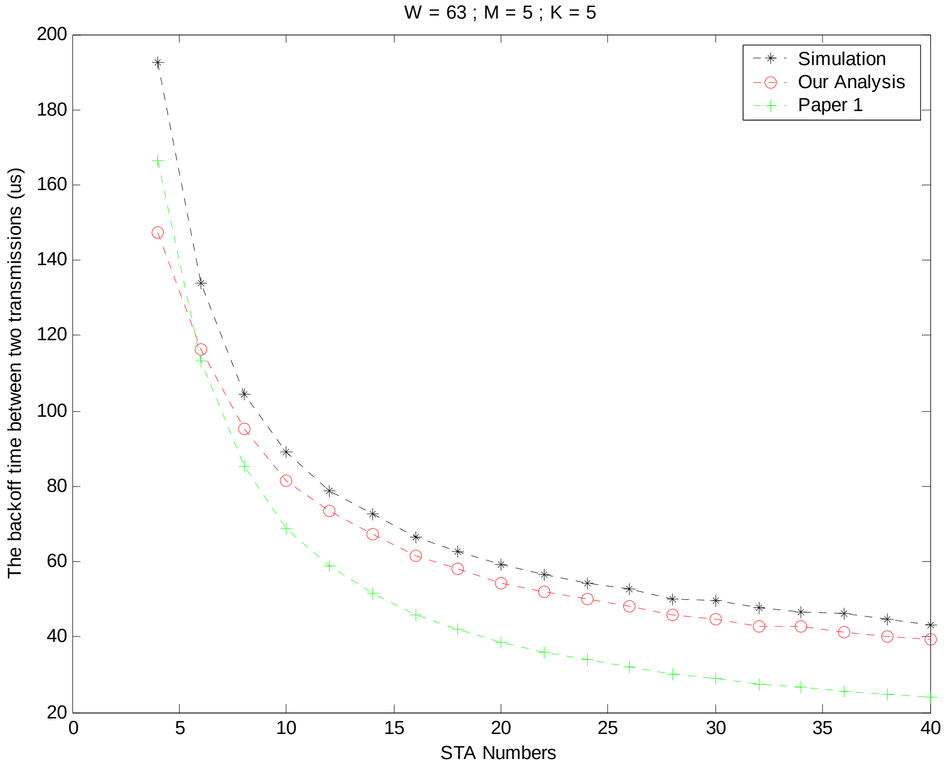

Fig.6-12 $W_{EmptySlots}$ for bidirectional traffic flow (W=63; M=5; K=5)

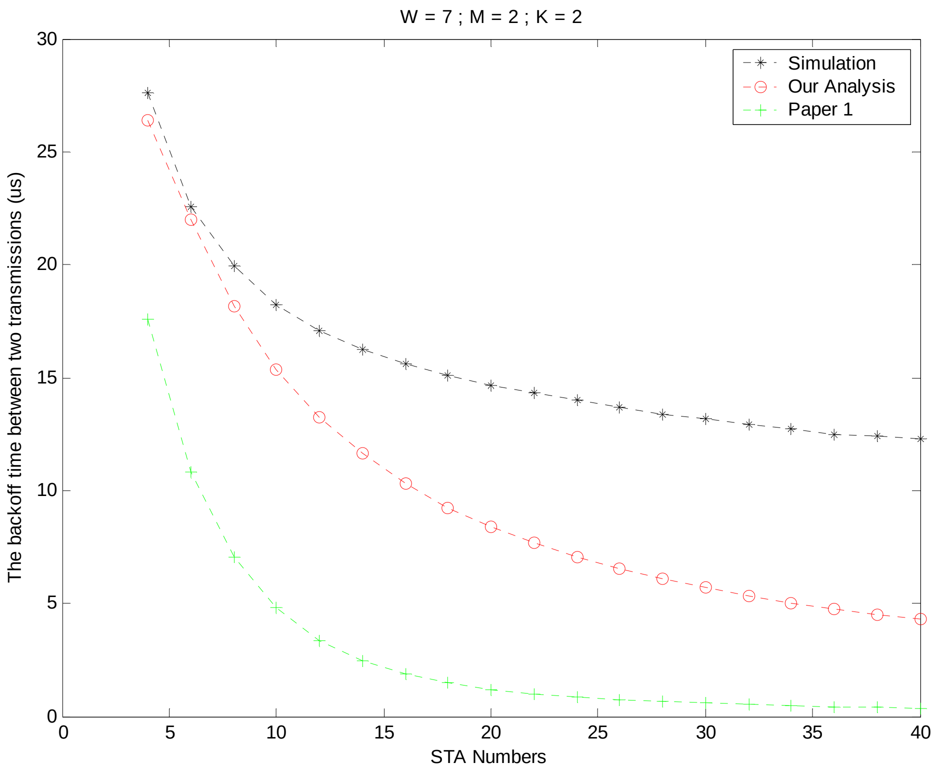

Fig.6-13 $W_{EmptySlots}$ for bidirectional traffic flow (W=7; M=2; K=2)

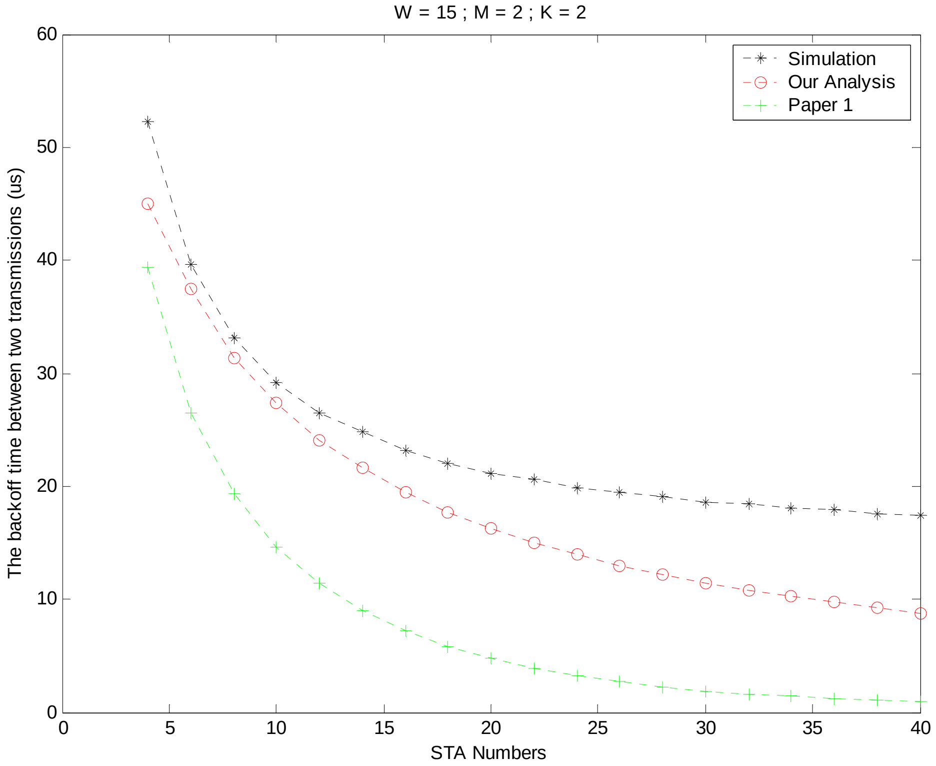

Fig.6-14 $W_{EmptySlots}$ for bidirectional traffic flow (W=15; M=2; K=2)

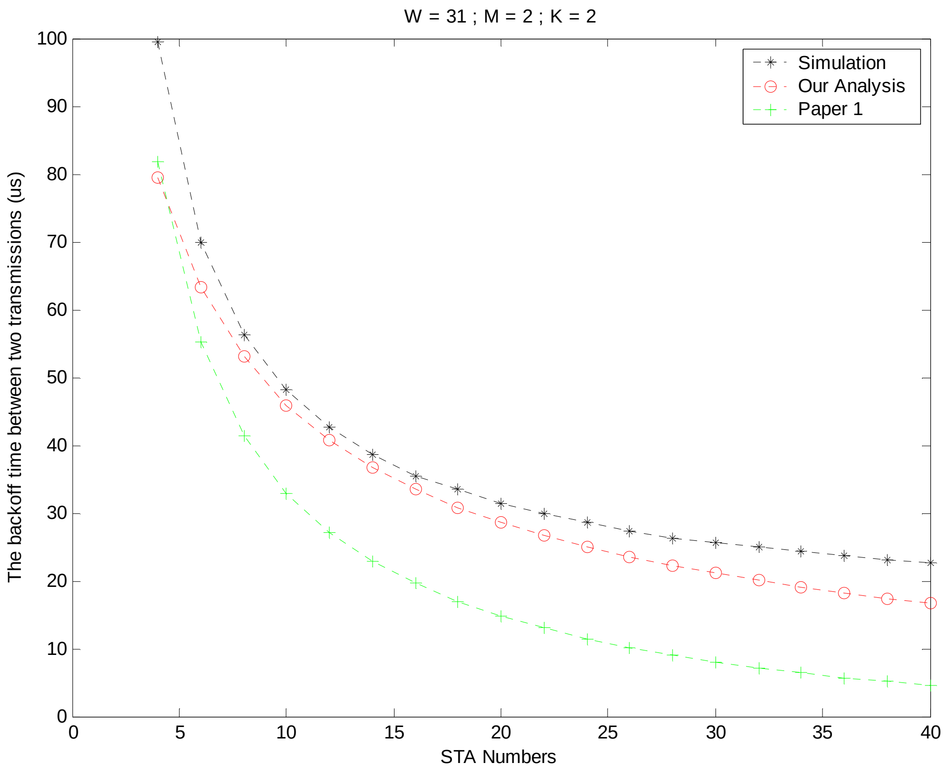

Fig.6-15 $W_{EmptySlots}$ for bidirectional traffic flow (W=31; M=2; K=2)

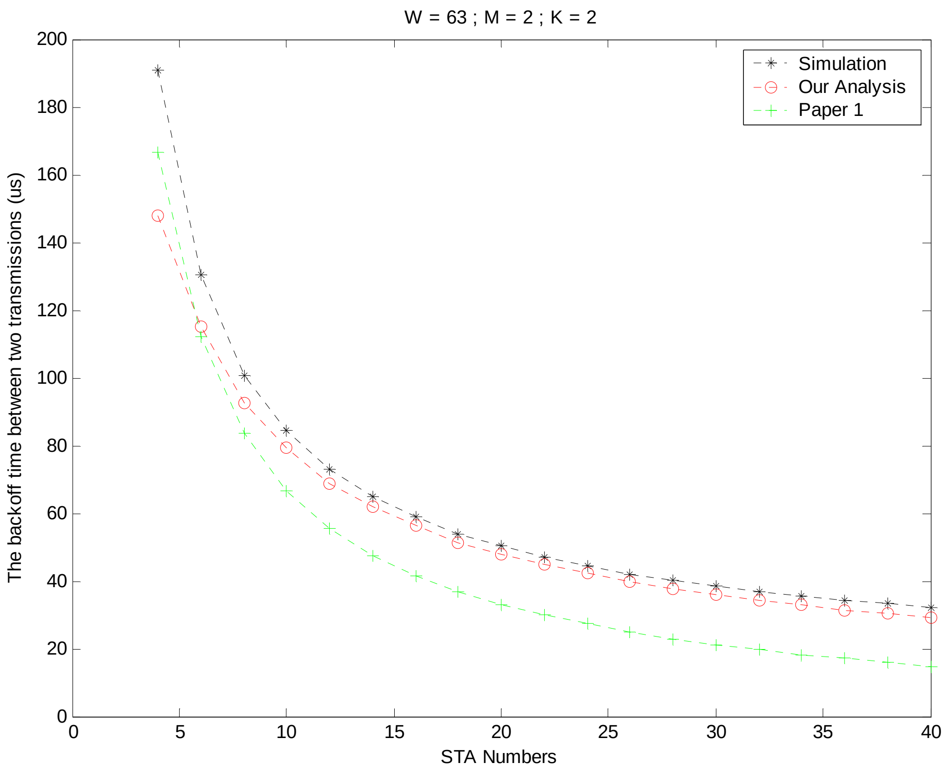

Fig.6-16 $W_{EmptySlots}$ for bidirectional traffic flow (W=63; M=2; K=2)

6-3 The channel utilization in the saturated WLAN that only supports unidirectional traffic flow.

We use the parameters of table 1 into the equations (4.3) and (4.17).

$$\mu_{paper1} = \frac{mac\_data}{mac\_data + \frac{11}{8}\left\{\frac{W_{uni\_1}}{N} \times 20 + \frac{871 - 376p}{1-p}\right\}}$$

$$\mu_{OurAnalysis} = \frac{mac\_data}{mac\_data + \frac{11}{8}\left\{\frac{W_{EmptySlots\_OurAnalysis} \times 20 + 921 - 426p_{channel}}{1-p_{channel}}\right\}}$$

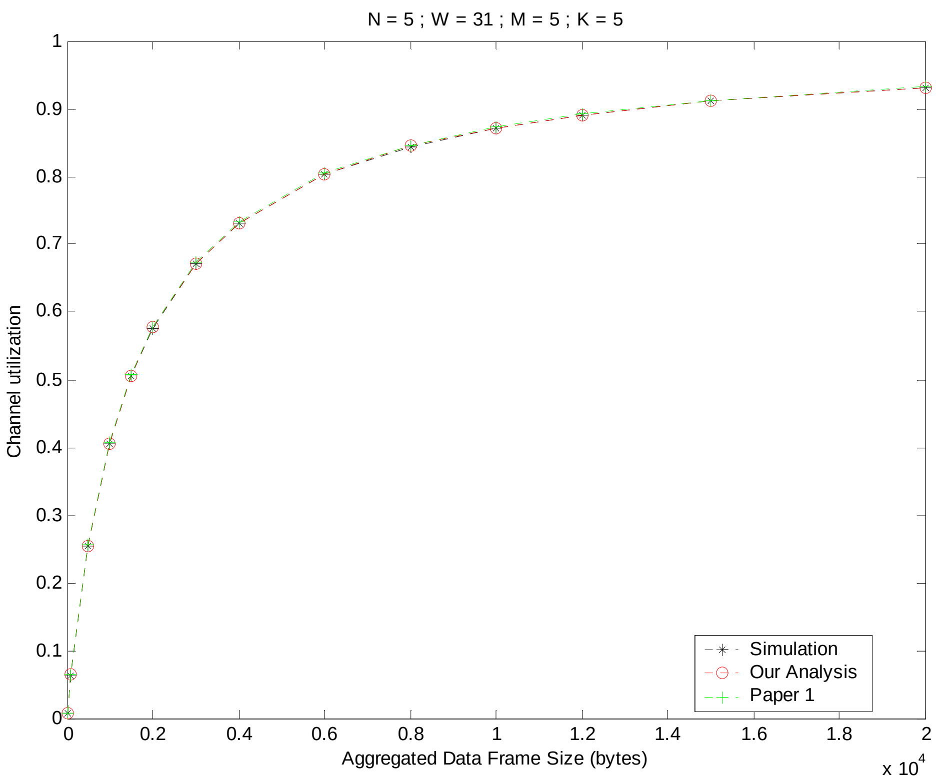

Fig.6-17 The channel utilization for unidirectional flow (N=5; W=31; M=5; K=5)

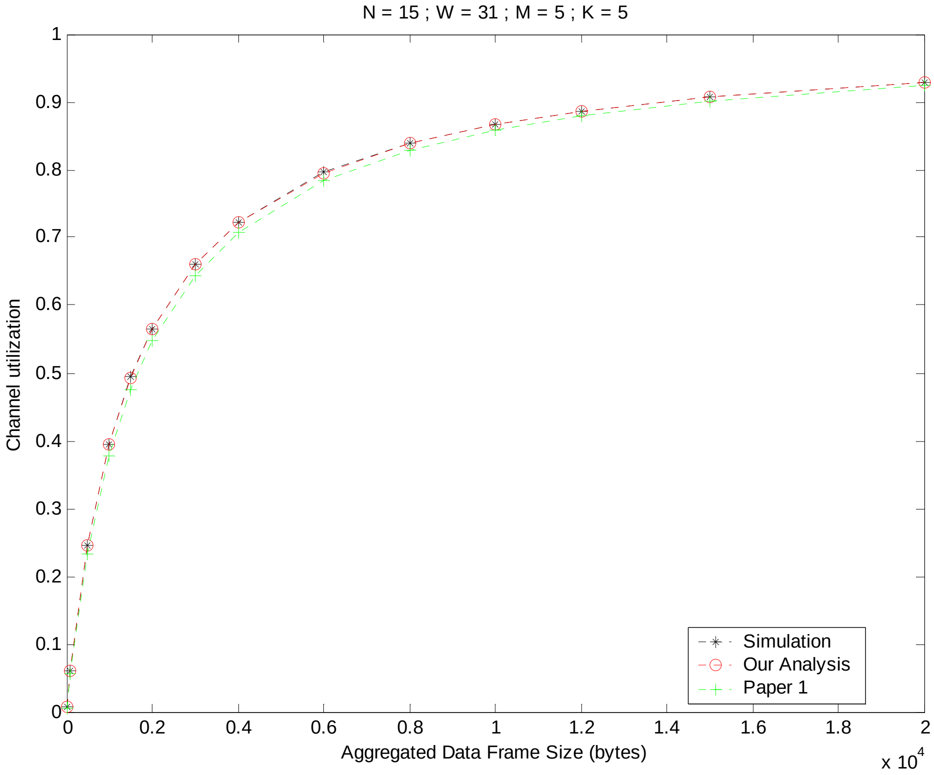

Fig.6-18 The channel utilization for unidirectional flow (N=15; W=31; M=5; K=5)

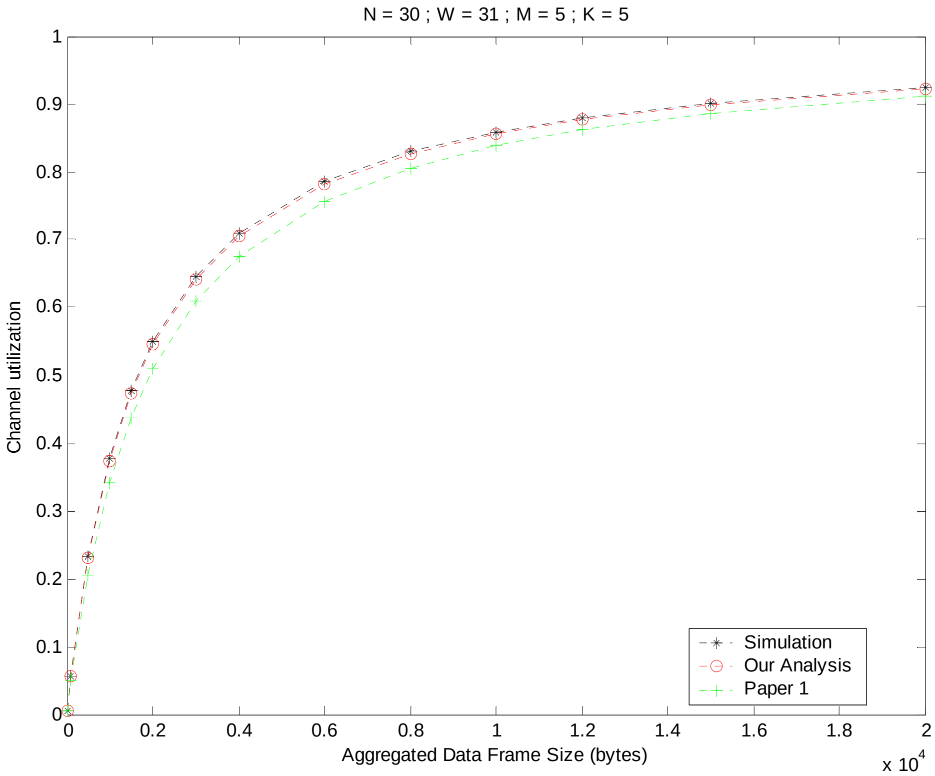

Fig.6-19 The channel utilization for unidirectional flow (N=30; W=31; M=5; K=5)

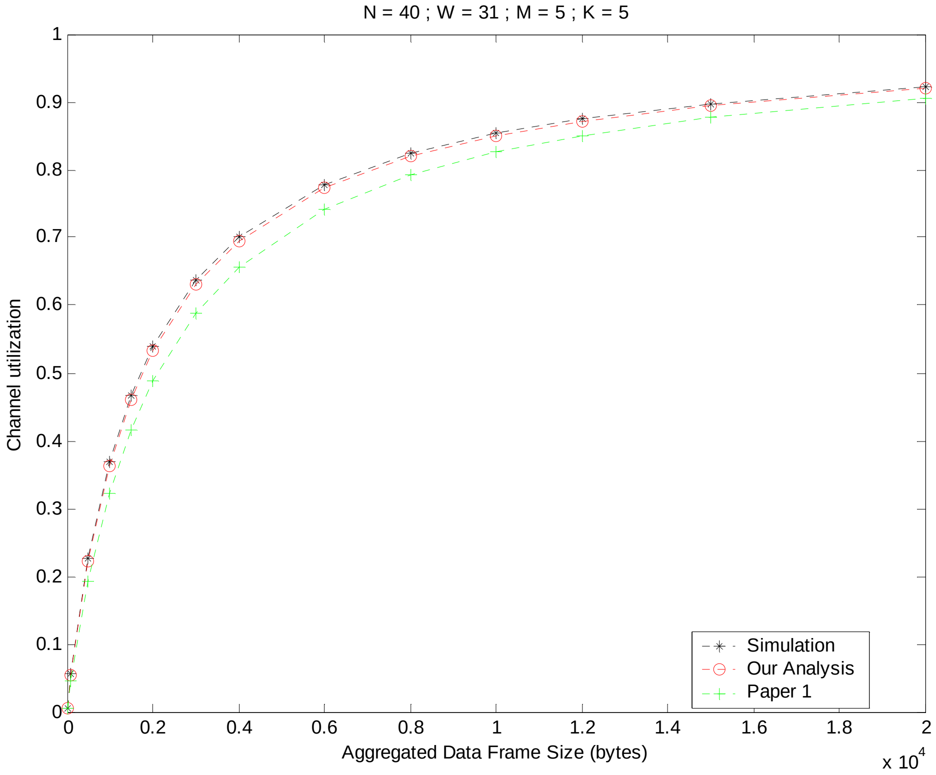

Fig.6-20 The channel utilization for unidirectional flow (N=40; W=31; M=5; K=5)

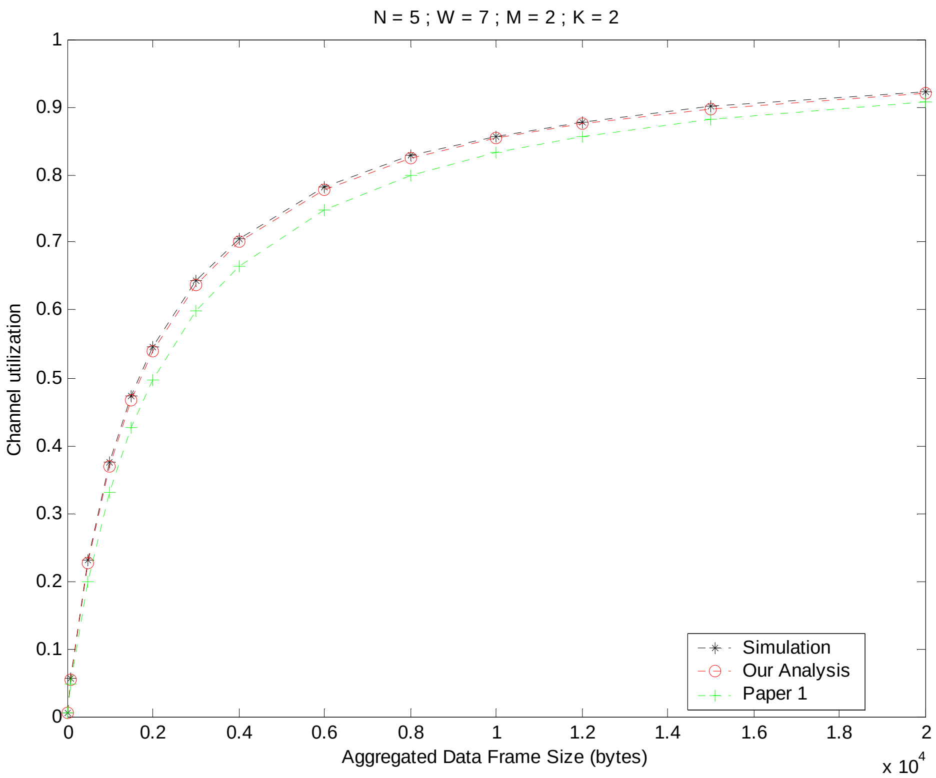

Fig.6-21 The channel utilization for unidirectional flow (N=5; W=7; M=2; K=2)

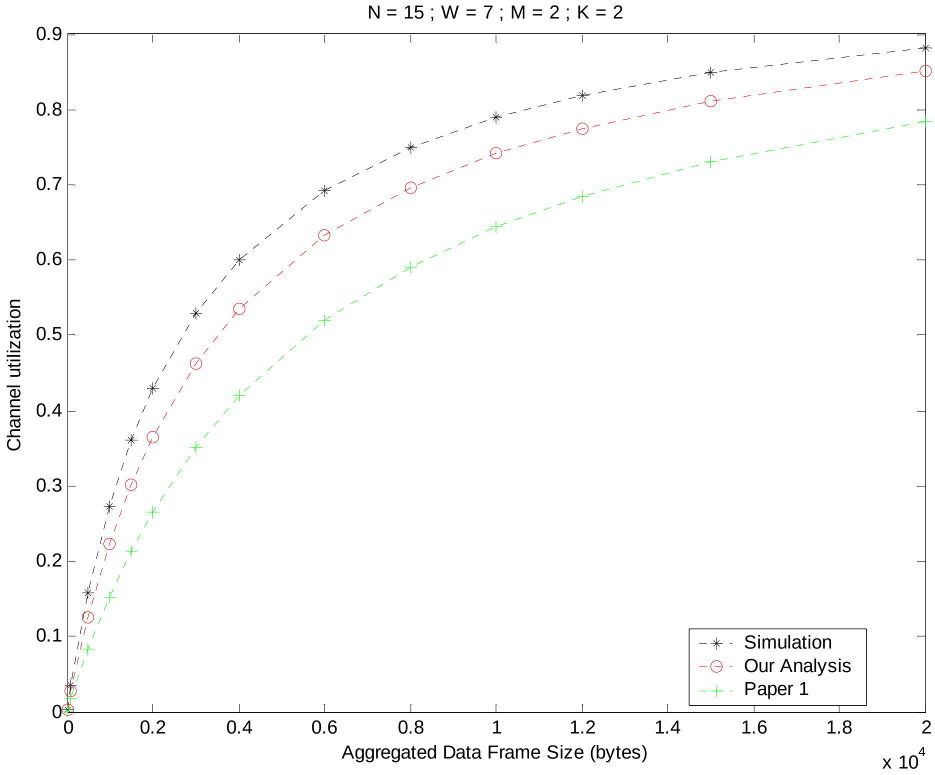

Fig.6-22 The channel utilization for unidirectional flow (N=15; W=7; M=2; K=2)

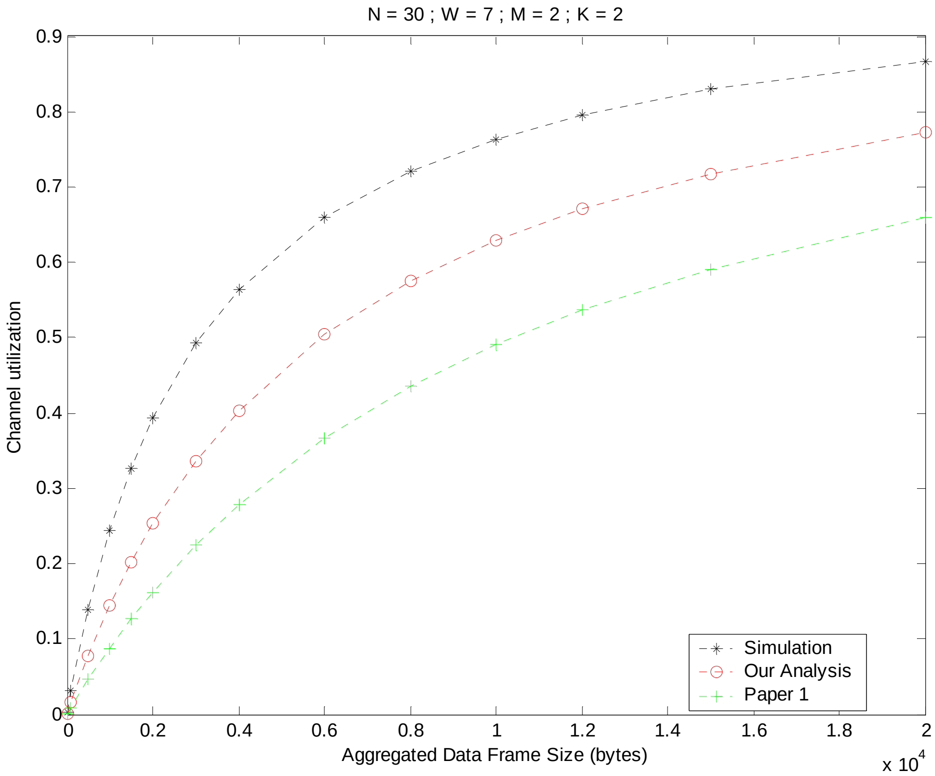

Fig.6-23 The channel utilization for unidirectional flow (N=30; W=7; M=2; K=2)

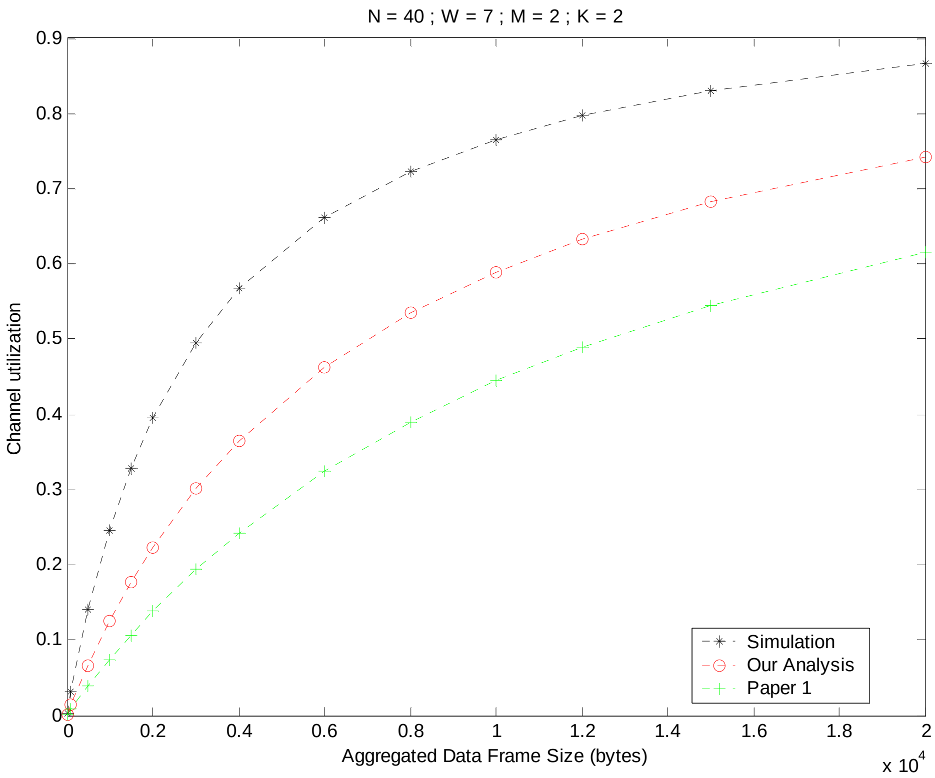

Fig.6-24 The channel utilization for unidirectional flow (N=40; W=7; M=2; K=2)

The relationship between $p_{channel}$ and p is $p_{channel} = \frac{p}{2-p}$, when we suppose one channel_collision_num contains two packet_collision_nums. But the case that one channel_collision_num contains three, four or more packet_collision_nums is not considered here.

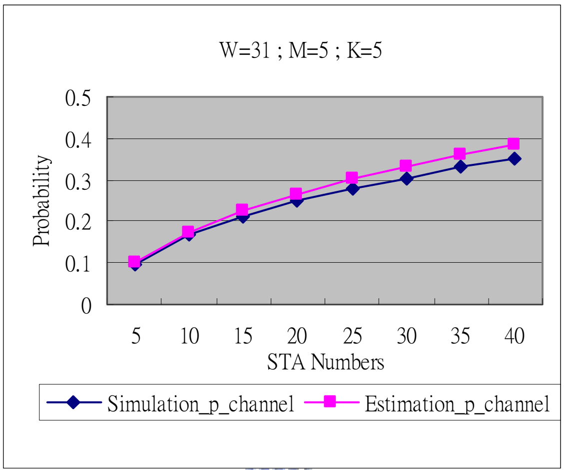

Fig.6-25 Simulation and Estimation for $p_{channel}$ (W=31; M=5; K=5)

N	Simulation_p_channel	Estimation_p_channel
5	0.09828	0.10066
10	0.1662	0.17424
15	0.21194	0.22543
20	0.24766	0.26532
25	0.27946	0.30138
30	0.3041	0.33034
35	0.33118	0.36055
40	0.35208	0.38538

Table 6-3 Simulation and Estimation for $p_{channel}$ (W=31; M=5; K=5)

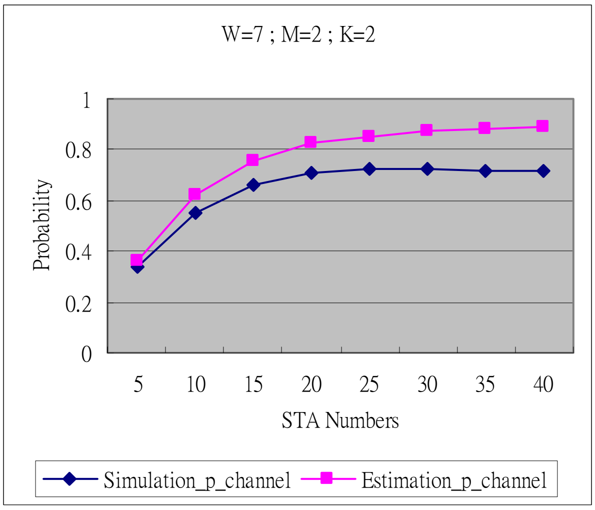

Fig.6-26 Simulation and Estimation for $p_{channel}$ (W=7; M=2; K=2)

N	Simulation_p_channel	Estimation_p_channel
5	0.33758	0.36513
10	0.5508	0.62386
15	0.65944	0.75827
20	0.70658	0.82304
25	0.72096	0.85433
30	0.724	0.87225
35	0.7192	0.882810
40	0.71562	0.89151

Table 6-4 Simulation and Estimation for $p_{channel}$ (W=7; M=2; K=2)

6-4 The channel utilization in the saturated WLAN that supports bidirectional traffic flow.

We use the parameters of table 1 into the equations (5.1) and (5.9).

$$\mu_{paper1} = \frac{2 \times mac\_data}{2 \times mac\_data + \frac{11}{8}\left\{ \frac{W_{uni}}{N-1} \times \frac{2N-4}{2N-3} \times 20 + \frac{1074 - 579p}{1-p} \right\}}$$

$$\mu_{OurAnalysis} = \frac{2 \times mac\_data}{2 \times mac\_data + \frac{11}{8}\left\{ \frac{W_{EmptySlots\_OurAnalysis} \times 20 + 1124 - 629 p_{channel}}{1 - p_{channel}} \right\}}$$

where mac_data is the aggregated frame size per direction

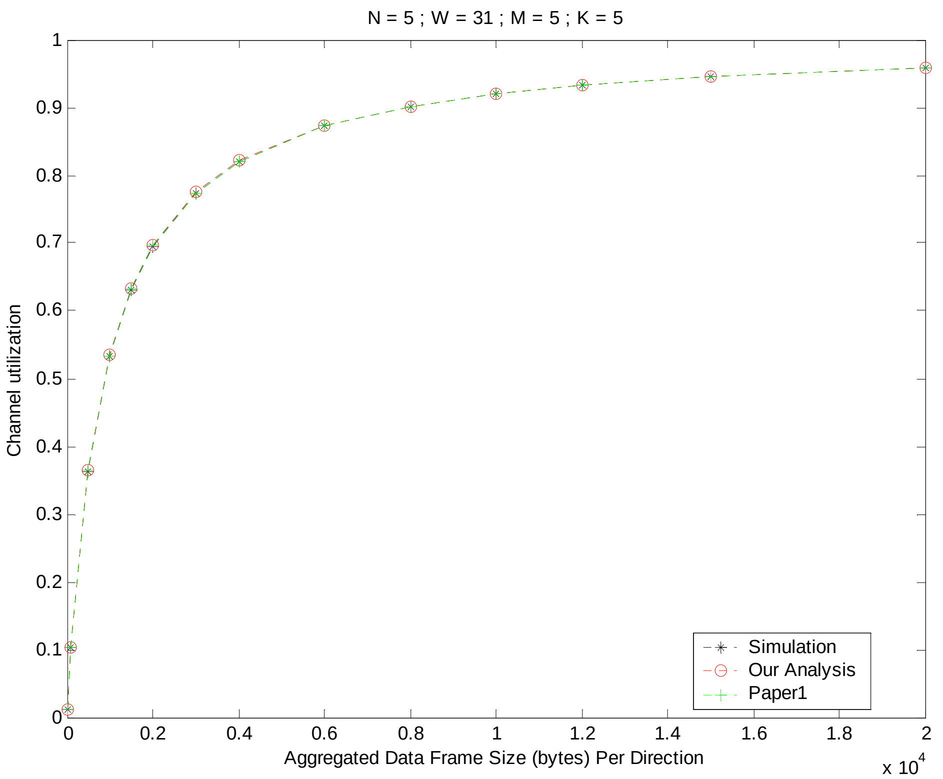

Fig.6-27 The channel utilization for bidirectional flow (N=5; W=31; M=5; K=5)

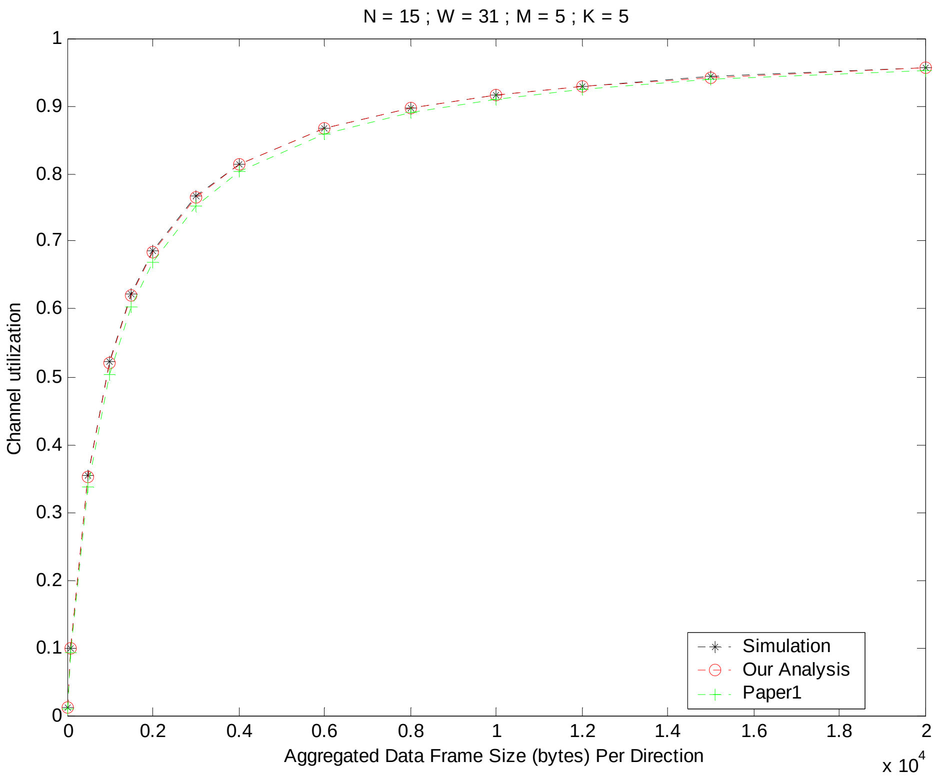

Fig.6-28 The channel utilization for bidirectional flow (N=15; W=31; M=5; K=5)

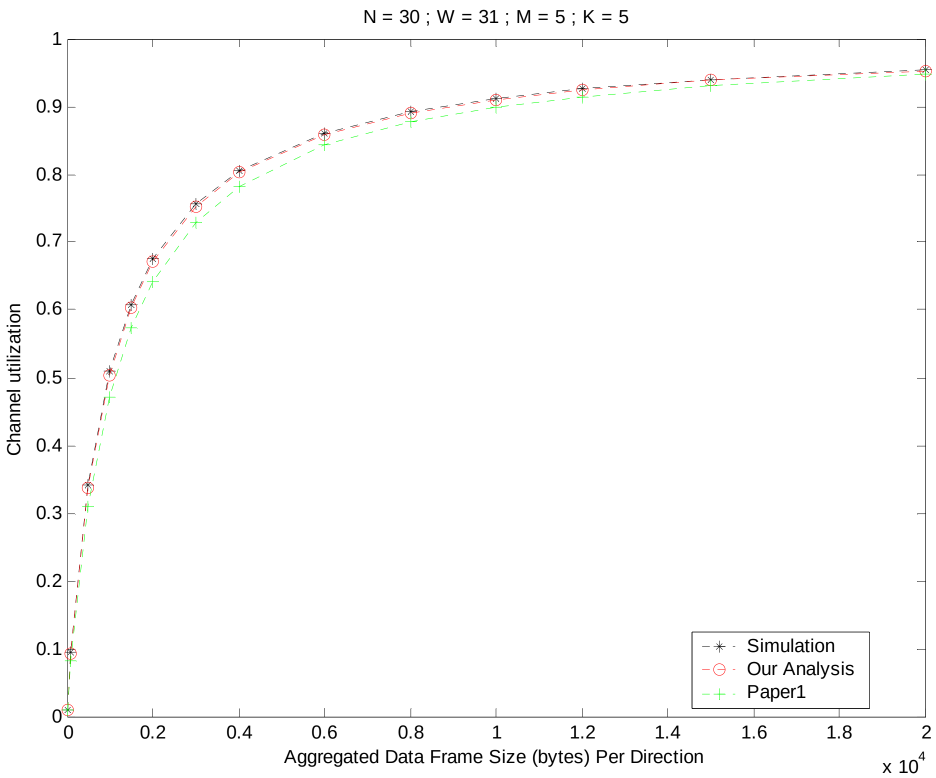

Fig.6-29 The channel utilization for bidirectional flow (N=30; W=31; M=5; K=5)

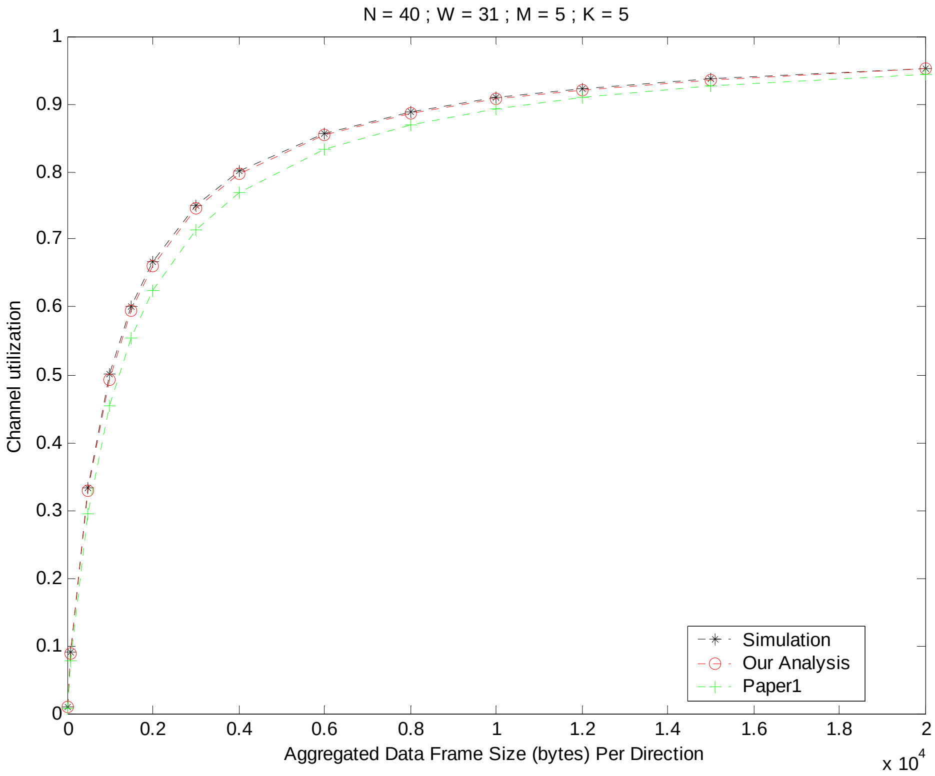

Fig.6-30 The channel utilization for bidirectional flow (N=40; W=31; M=5; K=5)

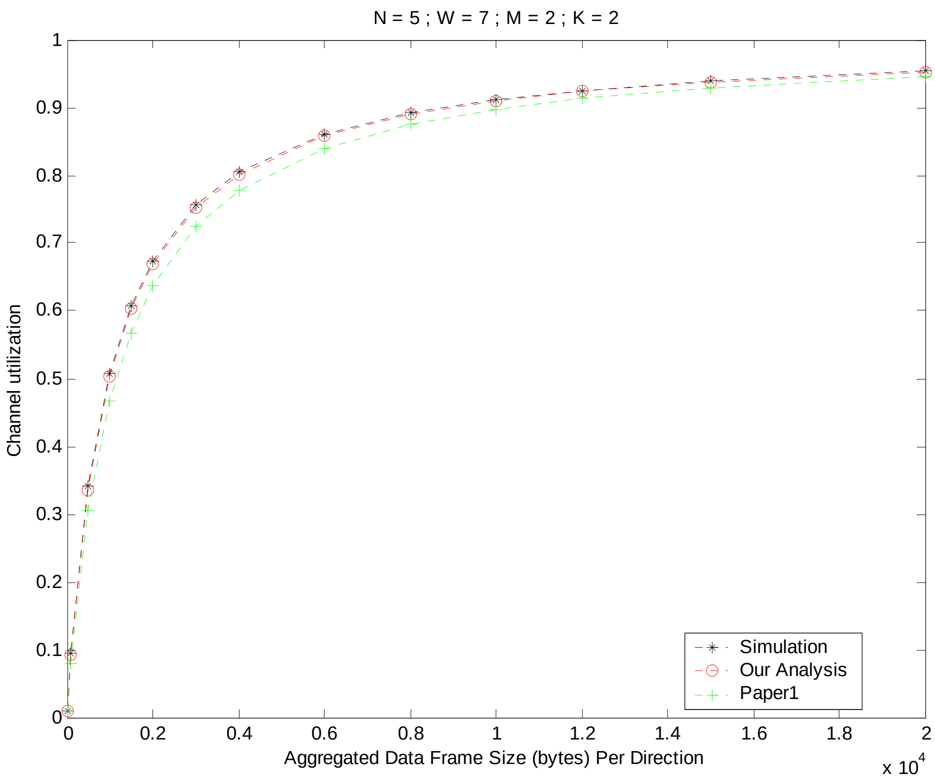

Fig.6-31 The channel utilization for bidirectional flow (N=5; W=7; M=2; K=2)

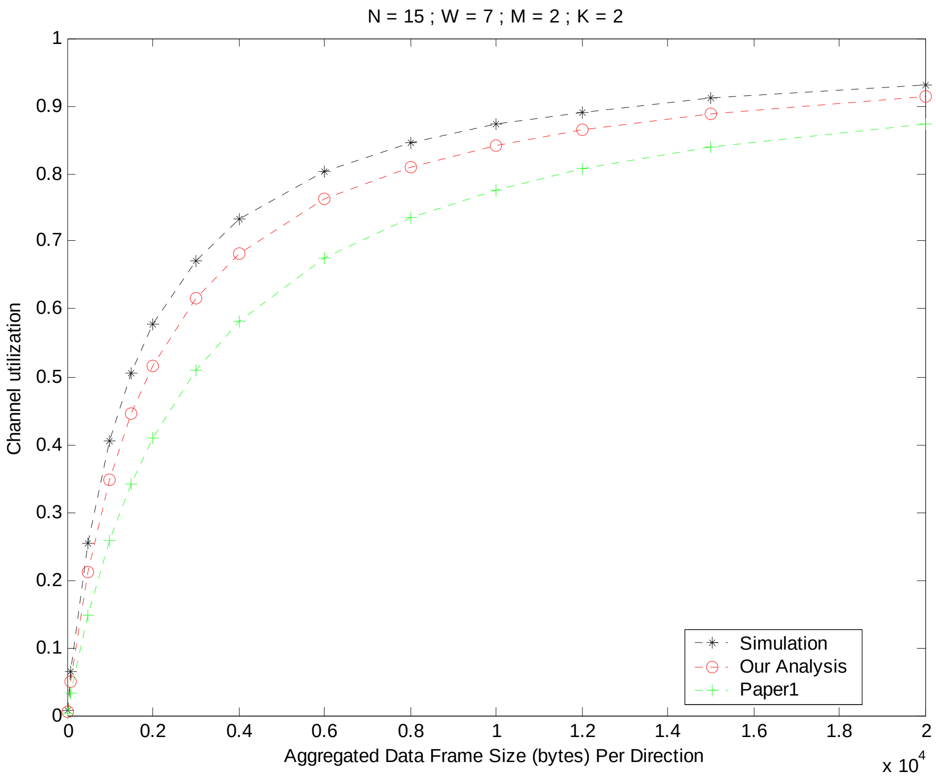

Fig.6-32 The channel utilization for bidirectional flow (N=15; W=7; M=2; K=2)

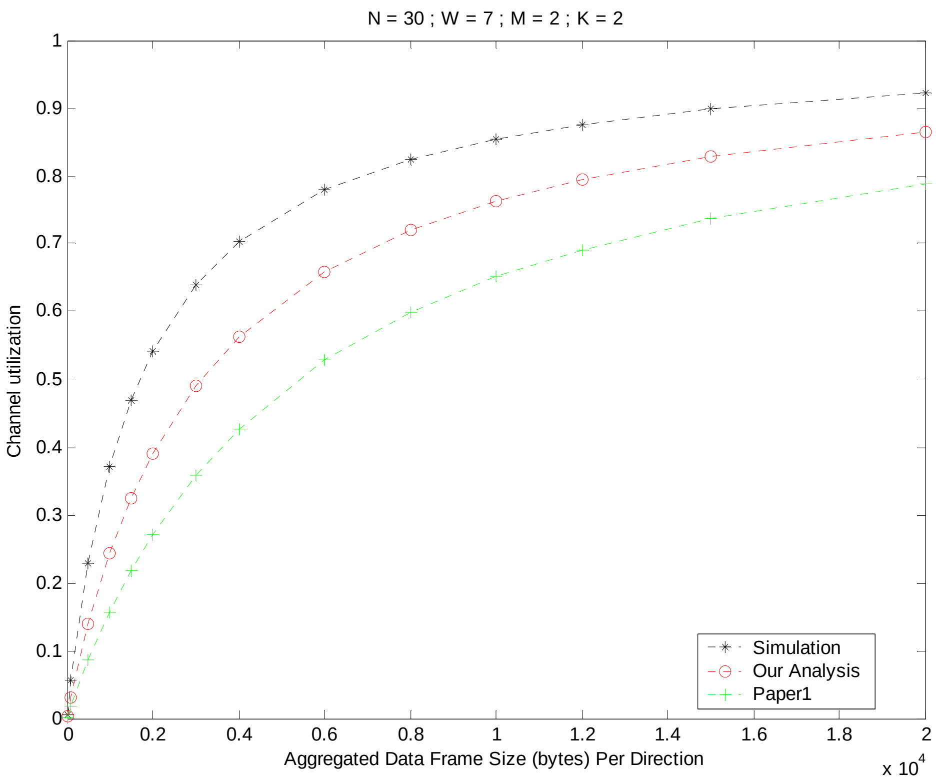

Fig.6-33 The channel utilization for bidirectional flow (N=30; W=7; M=2; K=2)

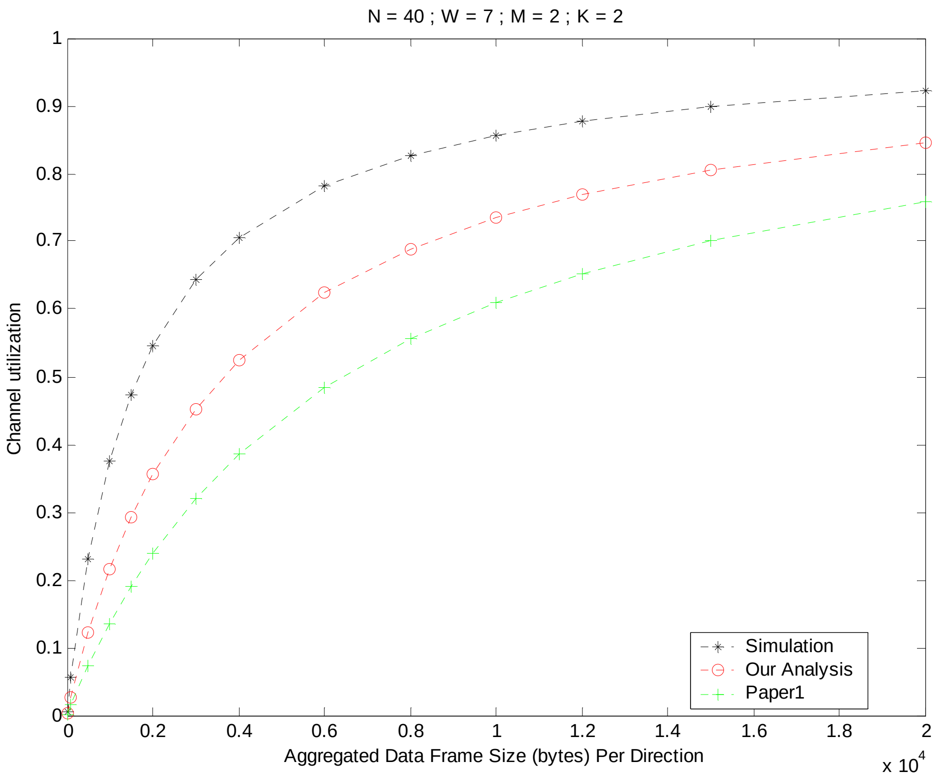

Fig.6-34 The channel utilization for bidirectional flow (N=40; W=7; M=2; K=2)

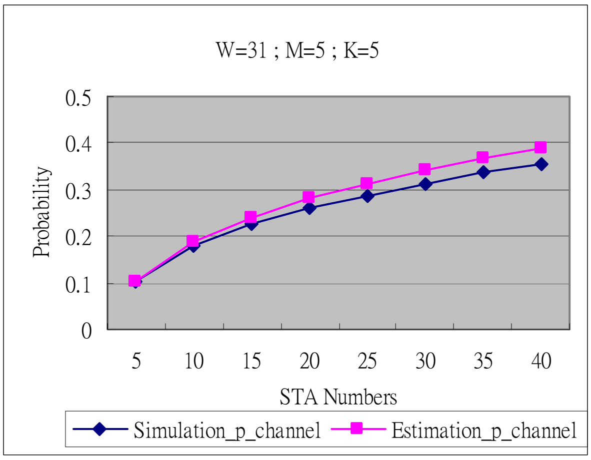

Fig.6-35 Simulation and Estimation for $p_{channel}$ (W=31; M=5; K=5)

N	Simulation_p_channel	Estimation_p_channel
5	0.10087	0.10341
10	0.17844	0.1873
15	0.22502	0.23966
20	0.26131	0.28043
25	0.28716	0.31067
30	0.31409	0.34177
35	0.3366	0.36762
40	0.35568	0.3906

Table 6-5 Simulation and Estimation for $p_{channel}$ (W=31; M=5; K=5)

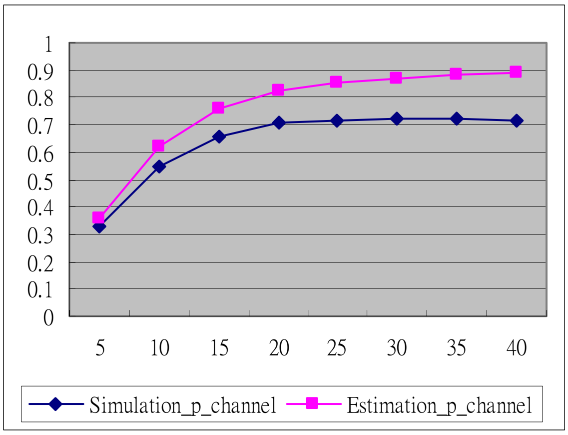

Fig.6-36 Simulation and Estimation for $p_{channel}$ (W=7; M=2; K=2)

N	Simulation_p_channel	Estimation_p_channel
5	0.33189	0.35775
10	0.54858	0.62131
15	0.65858	0.75748
20	0.70562	0.82212
25	0.71823	0.85215
30	0.72038	0.87025
35	0.72105	0.88352
40	0.71814	0.89253

Table 6-6 Simulation and Estimation for $p_{channel}$ (W=7; M=2; K=2)

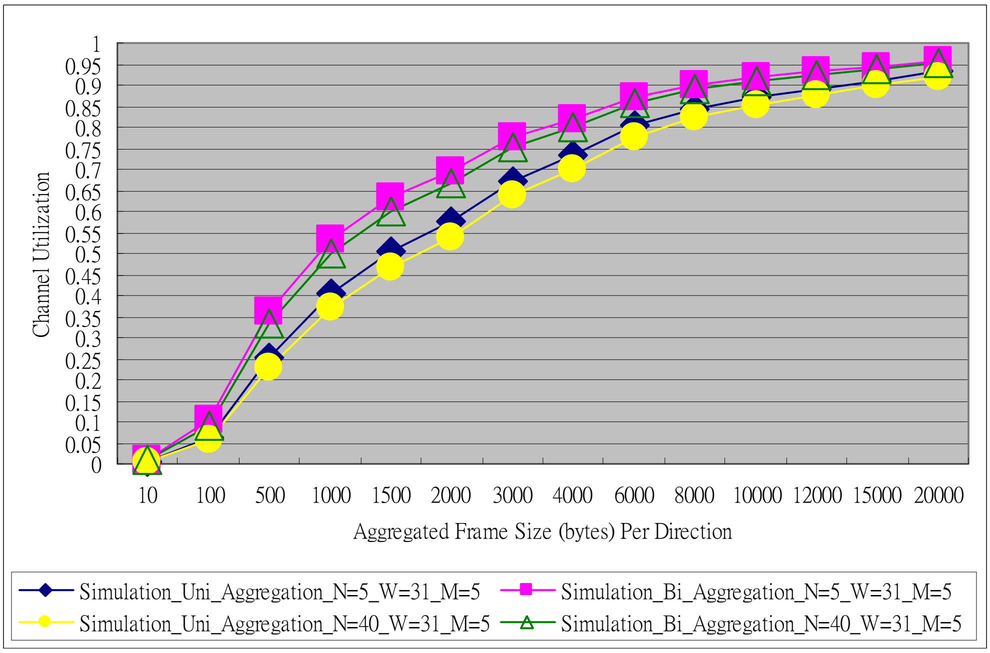

Fig.6-37 Comparison of channel utilization for N=5 and N=40 (W=31; M=5)

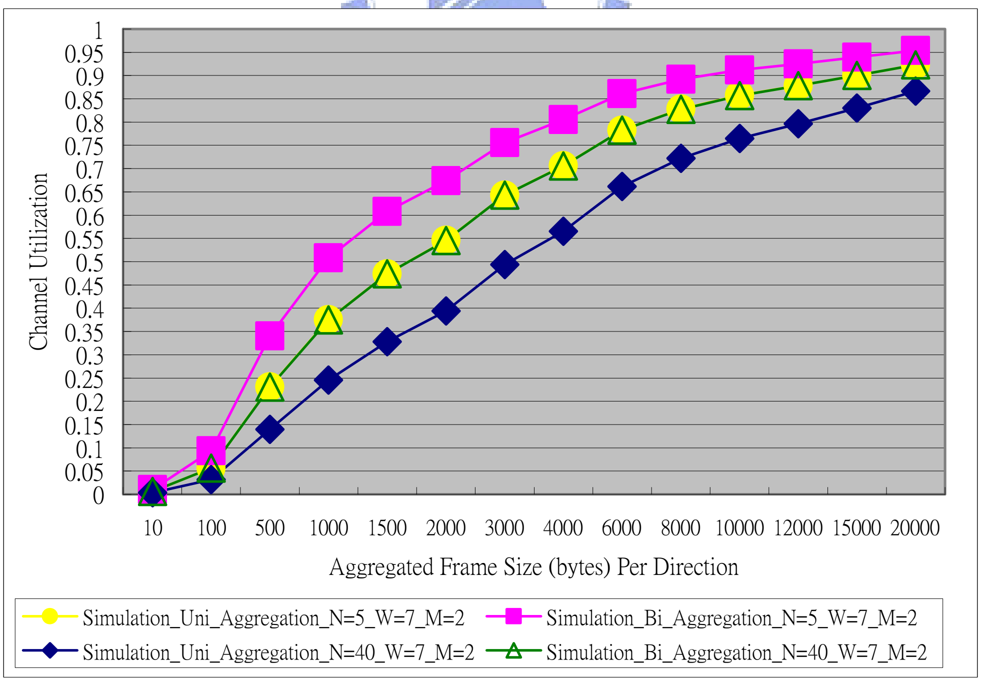

Fig.6-38 Comparison of channel utilization for N=5 and N=40 (W=7; M=2)

Chapter 7

Conclusions

In this paper, we have presented an analytic model to calculate the channel utilization for the 802.11 WLAN with unidirectional and bidirectional aggregation. Although the final equation is not a close-form solution, it is easy to calculate by bisection method. Simulation results shows that our estimation for W_e is more accurate and hence the estimated throughput is accurate too. This model can help to understand the performance of aggregation. We can see the benefit of bidirectional aggregation in utilization. However, the drawback is packet delay if aggregated frame is too large. We will extend our work to take account delay constraint for frame aggregation.

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