國立臺灣大學電機資訊學院電信工程學研究所

碩士論文

Graduate Institute of Communication Engineering

College of Electrical Engineering & Computer Science

National Taiwan University

Master Thesis

無線網路中以機器學習方法為基礎的新穎速率適應演算法

A Novel Rate Adaptation Algorithm via Machine Learning Approaches for Wireless Networks

陳贊羽

Zan-Yu Chen

指導教授：林宗男 博士

Advisor: Tsung-Nan Lin, Ph.D.

中華民國 98 年 7 月

July, 2009

國立臺灣大學碩士學位論文
口試委員會審定書

無線網路中以機器學習方法為基礎的新穎速率適應演算法
A Novel Rate Adaptation Algorithm via Machine Learning Approaches for Wireless Networks

本論文係陳贊羽君（R96942099）在國立臺灣大學電信所完成之碩士學位論文，於民國 98 年 7 月 15 日承下列考試委員審查通過及口試及格，特此證明

口試委員：

林宗男（簽名）

（指導教授）

蔡子傑　　陳俊良

系主任、所長　王暉（簽名）

誌謝

兩年的碩士生涯在口試結束的剎那，到達了尾巴，感謝指導教授林宗男老師，在碩一開學前收留了我，並且在這二年中不時的召喚和教導，不厭其煩的憚述著老師心中的人生大道理，令人受益匪淺、回味無窮。

在苦悶的研究生生活同時，也感謝一起打牌的 keter、昊呆、歐肥、curve 和小魚，在實驗室一起拉琴的震謙，拉著大家玩魔獸的浩儒，安排聚餐的林威，和四個學弟的幫忙，雖然有的很吵、有的身體不好、有的愛嗆我、有的愛傻笑，至少給日常的生活添了點不一樣的氣氛，自然還有兩個大學長柏江和士豪這兩年來的照顧，兩個人撐起來整間 Lab 507，還有感謝光為留下的研究題目。

再來，感謝兩位口試委員陳俊良和蔡子傑教授，不遠千里前來參加我們的口試，因為你們的建議和批評，讓論文更加臻完善。

最後，感謝我的父母從小到大給了我極大的自由，並且不辭辛勞的培育我完成了大學和研究所的課業，更在當初決定就讀電信所時，尊重並支持我的決定，讓我不必煩惱課業之外的事情，專心於研究的課題。

陳贊羽 謹誌

2009 年 6 月

中文摘要

IEEE 802.11 無線網路在最近幾年中成為了最受歡迎的無線網路技術，IEEE 802.11 支援了許多不同的傳輸速率，因此如何去決定一個適當的傳輸速率是一個挑戰，在這篇論文中，我們提出了一個新穎的速率演算法來解決這個問題，我們利用了 Maximum Likelihood Estimator 來穩健的預測出每一個速率的傳輸統計量，再來我們利用了在 PHY 層和 MAC 層兩個跨層的關系來決定每一個速率的傳輸代價。我們設計的目標是希望達到最大的頻譜使用效率，根據我們嚴謹的模擬結果，我們所提出的演算法比現存知名的演算法有更佳的表現。同時，WMNs (Wireless Mesh Networks)在過去幾年中擁有可觀的成長，而 WMNs 的效能決定在路由演算法和速率適應演算法，而各種不同的路由演算法效能已經在各種文獻中被深度的研究，然而速率適應演算法在 WMNs 中卻只有少量的研究，因此這篇論文也同時把我們所提出的演算法，實現在 WMNs 中，也同時比較各種演算法在 WMNs 中的表現，經由模擬結果，我們所提出的演算法在 WMNs 的環境下，同樣擁有傑出的效能。

關鍵字：自應性調變、速率控制、無線網路、IEEE 802.11、WMN


國立臺灣大學
敦品勵學
愛國愛人

Abstract

In recent years, IEEE 802.11 wireless networks have become the most popular wireless technology. IEEE 802.11 supports multiple transmission rates. How to determine the appropriate transmission rate is challenging. In this paper, we propose a novel rate adaptation algorithm to tackle this problem. We utilize the maximum likelihood estimator to robustly predict the transmission statistics for each transmission rate. Then we exploit the cross-layer correlation between PHY and MAC to determine the transmission cost for each transmission rate. The goal of our design is to achieve the maximum spectral efficiency. Based on extensive simulation experiments, the proposed algorithm outperforms existing well-known algorithms. Wireless mesh networks (WMNs) have experienced an enormous growth over the past few years. The performance of WMNs depends on the joint effect of both routing algorithms and rate adaptive algorithms. The performance of various routing algorithms has been studied extensively in the literature. However, little work has been done to evaluate the cross-layer impact of rate adaptive algorithms in WMN environments. In this paper, we compare the performance of several rate adaptive algorithms to exploit the multi-hop performance in WMN environments. In addition, a novel rate adaptive algorithm is proposed via the machine learning approach to robustly reflect the channel information. The goal of our design is to maximize the spectral efficiency. Through extensive computer simulations under different channel and topology environments, experimental results demonstrate the proposed algorithm outperforms other existing algorithms in WMN environments.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction

In recent years, IEEE 802.11 [1] Wireless Local Area Networks (WLANs) have become the most popular technology due to the wide deployment in many areas, such as home, office, airport, and so on. IEEE 802.11 [1] standards define Medium Access Control (MAC) layer and Physical layer (PHY) specifications. IEEE 802.11 [1] PHY supports multiple transmission rates by different Modulations and Coding Schemes (MCS). For example, in 802.11b, 4 data rates, 1 Mbps, 2 Mbps, 5.5 Mbps, and 11 Mbps, are provided at 2.4 GHz band. IEEE 802.11g PHY offers 12 data rates from 6 Mbps to 54 Mbps at 2.4 GHz band.

802.11-based wireless mesh networks (WMNs) have experienced an enormous growth over the past few years. A mesh network consists three components: Mesh Point (MP), Mesh Portal (MPP) and Mesh Access Point (MAP) according to IEEE 802.11s mesh standard (in draft) [2]. MP supports the mesh services of control, management, and operation of the mesh network. A mesh point which connects mesh networks to other networks is called MPP. And if MP also functions like an Access Point (AP), it is called MAP. The performance of WMNs depends on both the routing policy and the transmission rate. The routing policy is a critical subject in mesh networks [3–5]. In mesh networks, the route for a station to forward data may have a lot of options. In some sense, choosing a distinct route to forward data would lead to different performances. The performances of various routing policies have been studied extensively in the literature. However little work has been done to exploit the cross-layer impact of rate adaptive algorithms in WMNs.

How to pick the most suitable rate is a challenging task since the highest rate may not guarantee the highest throughput. Wireless channel conditions change in time creating random fluctuations of received signal power level because of the multipath, noise, and host mobility. If the chosen rate is too high, the transmitted packet may be failed due to the corruption; on the other hand, selecting a too conservative rate may degrade the throughput significantly.

The rate adaptive algorithm is still left unspecified by IEEE 802.11 standards. If a station incorrectly chooses the data rate, the total throughput of a system will be significantly degraded due to the phenomenon of performance anomaly [6]. Existing algorithms can be classified into two categories: Signal-to-Noise-Ratio (SNR) based approaches [7] and the statistic-based approaches [8, 9]. However, it is reported recently [10, 11] that there is little correlation between measured SNR and the transmission statistics in MAC layer. That is, it is difficult to derive the reliable transmission rate based on the information of SNR. Recently, several well-known algorithms, including Automatic RateFallback (ARF) [8], Adaptative ARF (AARF) [12], Collision Aware Rate Adaptation (CARA) [13], Robust Rate Adaptation Algorithm (RRAA) [9], Stochastic Automata Rate Adaptation (SARA) [14], and SampleRate [11] are proposed using the statistics of the packet delivery in the MAC layer. Those solutions provide a practical design guideline and report good throughput performances in some testing scenarios. However, several studies [9,14] also point out the inadequacies of current rate adaptive algorithms. The inadequacies include the predefined thresholds [8], probe packets of accessing possible new rates [8,11,12], being unable to exploit the short-term channel gain in a dynamic fading environment [11], and the inefficiency in terms of the decision flexibility [9].

With the challenges associated with the rate adaptation in wireless 802.11 environments, we propose a novel approach to exploit the short-term characteristics of fading channels in order to achieve the maximum spectral efficiency. Our mechanism, first, utilizes a maximum likelihood estimator to a robust estimator to reflect the state of dynamic channels. Then the cross-layer correlation between Medium Access Control (MAC) layer and Physical layer (PHY) are exploited using the well-known two-dimensional Markov model [15]. Therefore, MCS achieving the maximum spectral efficiency can be chosen among all available transmission rates. Our design is designed to be adaptive and does not use any pre-defined thresholds. Additionally, our mechanism is a sender-based approach and is compatible with IEEE 802.11 standard. We evaluate the performances of various algorithms through extensive simulations to study the transmission characteristics. Experiments are performed using the commercially available simulator QualNet [16]. As shown by the experimental results, the proposed algorithm outperforms the existing algorithms.

Chapter 2

Related Work

2.1 ARF and AARF

Automatic Rate Fallback (ARF) [8] is the most well-known rate adaptation algorithm, which is used in Lucent Technologies WaveLAN-II networking devices. ARF uses consecutive ACKs, consecutive frame losses, or timeout to switch different rates. Adaptive ARF (AARF) [12], an extension of ARF, doubles the threshold of the consecutively successful ACKs. AARF can achieve a better performance in a stable environment. AARF reduces trials for a higher rate while may degrade the system performance. ARF and AARF use consecutive ACKs to raise the rate, but consecutive ACKs is not easy to achieve. Therefore those algorithms tend to choose MCSs with lower transmission rate. Besides, consecutive ACKs have less and less correlation with regard to the channel conditions in a multi-station environment.

2.2 CARA

Collision-Aware Rate Adaptation (CARA) [13], another extention of ARF, adopts RTS/CTS to effectively avoid collisions. If the first ACK is missed, RTS is enabled at the next frame. If the next transmission is still failed, the station will decrease the current rate; otherwise, the station will continue the current rate and disable RTS. The other operations of CARA are just like ARF.

2.3 RRAA

Robust Rate Adaptation Algorithm (RRAA) [9], proposed by Wong, sets two loss ratios to determine rates and an adaptive RTS filter is used. First, RRAA calculates two loss ratio thresholds, Maximum Tolerable Loss threshold (MTL) and Opportunistic Rate Increase threshold (ORI), for each rate according to the ratio of the transmission time between adjacent rates. Then RRAA sets the estimation window size for each rate. When the number of frames transmitted attains to the estimation windows size of the current rate, the station switches the rate in terms of the loss ratio in the window. If the ratio is larger than MTL, the station decreases the rate in the next window, whose size is set by the new rate. If the ratio is less than ORI, the station increases the rate in the next window. The rate remains the same in other cases. An estimation window is renewed if the timer expires because RRAA wants to keep the newest statistics in the record. In addition, RRAA uses adaptive RTS to avoid collisions. The concept is similar to CARA, but RRAA designs an RTS filter to turn on RTS filter. It can prevent from the drawback of RTS oscillation, which means RTS alternates between on and off.

2.4 SampleRate

SampleRate [11] is introduced by Bicket in his master thesis at MIT. SampleRate calculates the average transmission time of a packet for each rate, and switches the rate by choosing the rate with the minimum average time. SampleRate counts the transmission time in the packet level according to the retries. Per 10th packet, SampleRate will randomly choose a rate which has the transmission time less than the current rate to gather statistics of different rates. SampleRate gathers statistics in the past specified duration (e.g. 10 seconds). If there are four successive packets failed, SampleRate will freeze the rate until the statistics is obsolete.

2.5 SLA and SARA

SARA [14] and SLA [17] are using learning-automata to adjust the probability of each rate. At the first, each rate have the same probability, and then pick one rate according to the probability vector. If the transmission of the chosen rate is successful, SARA and SLA will increase the probability of this rate and decrease the others. If the channel is static, we believe SARA and SLA will converge into the best rate. However, the channel is time-varying, the best solution is changed depending on the channel dynamic. It may take time to find the new suitable rate while using the approach of learning-automata.

Chapter 3

Proposed Algorithm

In this paper, we propose a machine-learning-based rate adaption algorithm. The goal of our design is to achieve the maximum throughput. Throughput is defined as the amount of the error-free information that is delivered to the upper-layer of the destination communication system. Not only PHY layer but also MAC layer has an important effect on the throughput. Therefore the cross-layer correlation between MAC and PHY layers on the throughput should be considered. To achieve the maximum throughput, our algorithm is devised to have the following characteristics: 1) to quickly respond to changing wireless channels; 2) to avoid improper adjustment of the transmission rate. Additionally, to be compatible with IEEE 802.11 standard, our algorithm is a sender-based approach.

3.1 Cross-layer performance between MAC and PHY layers

Wireless channel conditions change in time creating random fluctuations of the received power level, or fading. Packets transmitted using Modulation and Coding Scheme (MCS) of high data rate may fail due to the corruption from bad channel conditions. If the number of failed transmissions is within the retry count, the packet will be retransmitted again. If the number of failed transmission is larger than the retry count, the packet will be dropped. And the packet drop probability P_{drop} is given as:

$$P_{drop} = P_c^{m+1}, \tag{3.1}$$

where P_c is the packet failed probability (which means a packet encounters either a corruption or a collision) and m is the retry limit. If the delay for a successfully transmitted packet is defined as the duration from the time the packet is at the front of MAC queue ready to be transmitted, until an acknowledgement for the packet is received [18]. The result can be calculated using the well-known Bianchi's two-dimensional Markov model [15, 18]. This model considers various aspects of CSMA/CA behaviors such as the retry count, binary exponential doubling the window length, dropping the packet etc. The main idea of the calculation is summarized below. For detailed calculation, please refer to [15, 18]. The average packet delay $E[D]$, which means this packet is transmitted, is given by:

$$E[D] = E[N_s] * E[T_{slot}]. \tag{3.2}$$

$E[N_s]$, the average number of slot times for successfully transmitting a packet, is given by:

$$E[N_s] = \sum_{i=0}^{m} \frac{(P_c^i - P_c^{m+1}) * \frac{W_i+1}{2}}{1 - P_c^{m+1}}, \tag{3.3}$$

where W_i is the contention window size at the backoff stage i. The average length of a slot time $E[T_{slot}]$ is equal to:

$$E[T_{slot}] = (1 - P_{tr}\sigma) + P_{tr} * P_s * T_s + P_{tr} * (1 - P_s) * T_c \tag{3.4}$$

Where σ is the duration of an empty slot time, P_{tr} is the probability that at least one station will transmit a packet and P_s is the probability for a packet which is successfully delivered. T_s and T_c denote the average times the medium is sensed busy because of a successful transmission or collision.

Therefore, the average transmission time to deliver a packet should be calculated as the total delays of the successfully transmitted packets plus the time duration which the packets are dropped divided by the successfully transmitted packets. Therefore, the average transmission time $E[T_t]$ can be computed as:

$$E[T_t] = E[T_{drop}] + E[T_D] \tag{3.5}$$

Where $E[T_{drop}]$, the average time to drop a packet, is equal to :

$$E[T_{drop}] = E[S_{drop}] * E[T_{slot}]. \tag{3.6}$$

Since a packet reaches the retry limit $m+1$ times, it will be discarded right away. And let the average number of the slot time required for a packet to be dropped is equal to:

$$E[S_{drop}] = \sum_{i=0}^{m} \frac{W_i + 1}{2} \tag{3.7}$$

Fig. 3.1 shows the average transmission time (Eq. 3.5) with respect to different packet failure probabilities.

3.2 Algorithm Description

Our algorithm can be denoted by $R_m(C, P(C))$ where R_m is the chosen transmission rate, C denotes an estimator of channel states, which is to predict the likelihood of success for each MCS promptly, and P_C denotes the decision policy to choose the rate. The devised mechanism is to maximize the spectral efficiency. That is to find the minimum average system transmission time t_m for a given MCS given the estimated channel information. In other words, our strategy of selecting MCSs can be described as:

$$R_m = \arg\min_m t_m \tag{3.8}$$

We utilize the technique of machine learning to robustly estimate the channel state. A maximum likelihood approach is devised to estimate the probability of a packet being transmitted successfully with respect to different transmission rates. When the information is available, the average transmission time can be obtained easily from the cross-layer analysis result of Fig. 3.1. The behavior of the packet transmission is treated as a random process. The outcome of the event in such a process is either success or failure. After modeling its behavior, a robust feature of the channel can be estimated as described below.

The pseudo code of the proposed algorithm can be summarized in Table 3.1

parameters

Tx_rate	the chosen transmission rate;
Tx_time_i	The transmission delay using rate i;
$Num[i]$	the number of using rate i in the past 100 frames;
$ACK[i]$	the successful transmission of using rate i in the past 100 frames;
$count$	determine when to chooses the rate;
$enableRTS$	record whether the RTS/CTS opened;

$recACK$	record whether ACK is missed;
$recCTS$	record whether CTS is received;

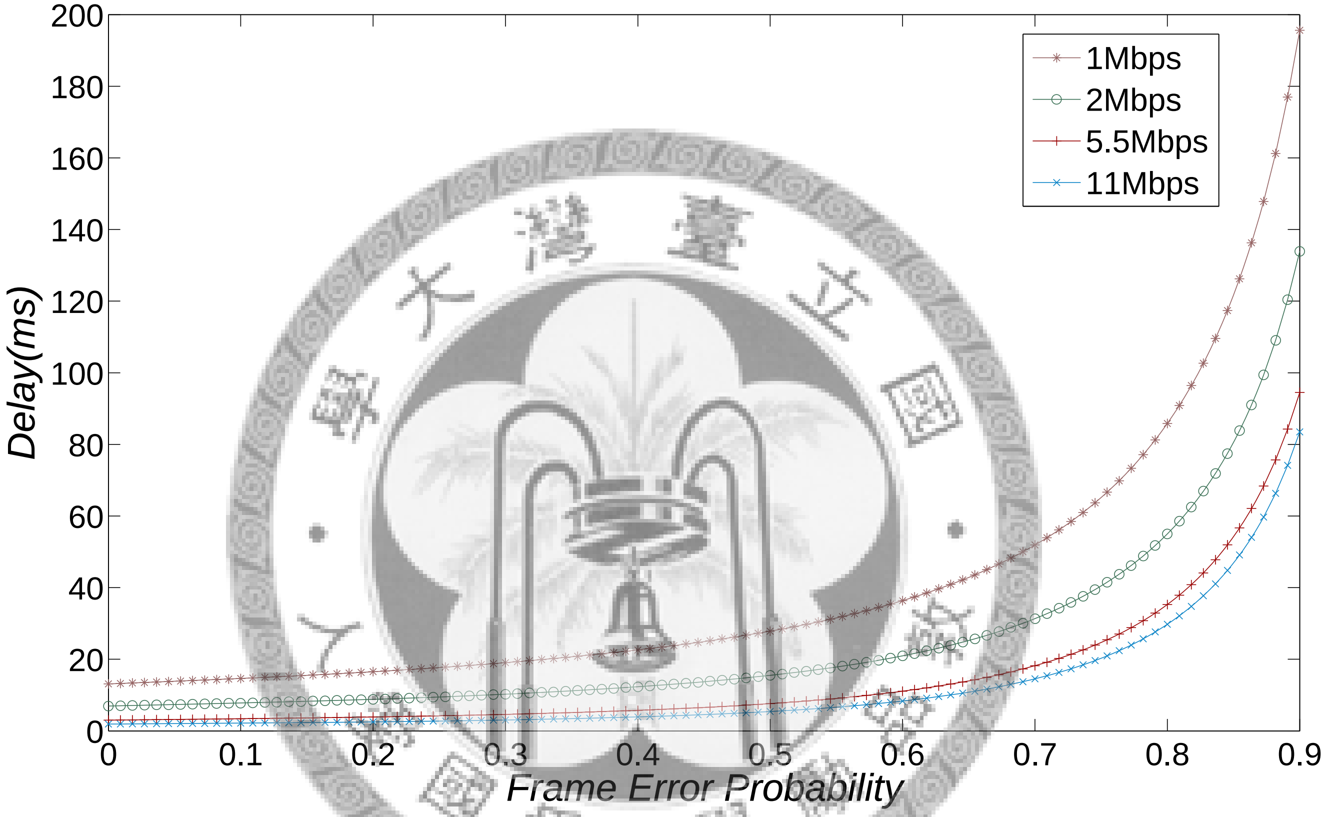

Figure 3.1: The average transmission time with respect to packet error probability for different MCSs.

3.3 Maximum Likelihood Estimator

There are two possible outcomes of a frame transmission, success s and failure f. The sample space contains two events, s and f. Let X be a random variable defined by $X(s) = 1$ and $X(f) = 0$. The frame success probability is defined as

Table 3.1: Main Steps of the proposed rate adaptive algorithm

Summary of the proposed algorithm

```
initialize: Num[i]=0,count=9,recACK=1,recCTS=0
repeat
  if ACK is missed then
    recACK = 0;
  if CTS is received then
    recCTS = 1;
  if recACK = 0 and enableRTS = 0 then
    start RTS/CTS;
    enableRTS = 1;
  if recCTS = 1 and enableRTS = 1 then
    finish RTS/CTS;
    enableRTS = 0;
  do i = 0 to 3
    if Num[i] = 0 then FSR[i] = 1;
    else FSR[i] = ACK[i]/Num[i];
    get $Tx\_time[i]$ from Fig.??;
  end
  if $count \neq 0$ then $count--$;
  else
    do i = 0 to 2
      if $Tx\_time[i] < Tx\_time[i+1]$ then
        $Tx\_rate = i$;
      else
        $Tx\_rate = i + 1$;
    $count = 9$;
  end
end repeat
```

the conditional probability that a frame transmission would be successful given a modulation and coding scheme MCS_i. It is denoted as $p_i = P(X = 1|MCS_i)$.

Suppose that there are m MCSs. When a station has a frame to transmit, we are interested in the frame success probabilities of this frame for all m MCSs. Although this frame is not transmitted yet, an estimated frame success probability $\hat{p_i}$ for $i = 1$,...,m could be obtained by a *maximum likelihood estimation* method.

The collected samples of X are separated according to each individual MCS, so that there are m sets, denoted as D_1,...D_m. Suppose that D_i contains n samples, $x_1, ..., x_n$. In D_i, α of the samples are 1's, and the others are 0's. Since the samples are obtained independently,

$$p(D_i|MCS_i) = \prod_{k=1}^{n} p(X = x_k|MCS_i) = p_i^{\alpha} \times (1 - p_i)^{(n-\alpha)} \tag{3.9}$$

We define a *log-likelihood* function $l(p_i)$ as

$$l(p_i) \equiv \ln p(D_i|MCS_i) = \alpha \ln p_i + (n - \alpha) \ln(1 - p_i) \tag{3.10}$$

The maximum likelihood solution could be written as the argument $\widehat{p_i}$ that maximizes the log_likelihood, i.e.,

$$\widehat{p_i} = \arg\max_{p_i} l(p_i). \tag{3.11}$$

Chapter 4

Simulation Set-up

We evaluate the performances of the proposed algorithm via extensive computer simulations using Qualnet 4.0, which provide many wireless protocols and channel models. [16]. We implement several well-known algorithms, such as AARF [12], CARA [13], RRAA [9], SampleRate [11], SLA [17], and SARA [14]. We take 802.11b as MAC protocol. For reality, several time-varying wireless channel models are considered. We use the two-ray ground reflection model as the large scale fading model and Rayleigh and Ricean fading model (with Ricean factor of 3) as the small scale fading model. We set the traffic CBR in a greedy mode, which means a station always has the data to send, at a duration of 100sec and the payload size is 1500 bytes. Four scenarios are devised to exploit the characteristics of rate adaptive algorithms: 1) single transmission link with the fixed distance 2) single transmission link with different distances; 3) several transmission links with the same distance in a infrastructure mode; 4) several transmission links with different distances and mobilities in an infrastructure mode. And then we evaluate the performance of each algorithms in 802.11-based mesh network. The topology of the wireless mesh network is shown in Fig. 4.1. Mesh Portal Point is placed at the black node (in the center of the leftmost stations). Three different distances between stations are chosen in order to evaluate the decision flexibility of various algorithms. Since the transmission range of 11 Mbps is about 340 meters, the experiments are performed in three scenarios of (1) 250 meters (the best fixed transmission rate is 11 Mbps), (2) 370 meters (the best fixed rate is 5.5 Mbps), and (3) the mixed distances of 250 and 370 meters. The distances are chosen because, for a single transmission link, the 11 Mbps performs the best in 250 meters and 5.5 Mbps is the best in 370 meters during a static channel condition.In addition, to exploit the responsiveness to sudden changes in channel conditions, three different channel models, including (1) large-scale fading, (2) Ricean fading with Ricean factor of 3 , and (3) Raleigh fading, are utilized. Constant Bit Rate traffic of a 1500-byte packet sent every 40 mili-second is adopted in the experiments. The simulation time for each scenario is 60 seconds and the routing protocol of AODV is applied.

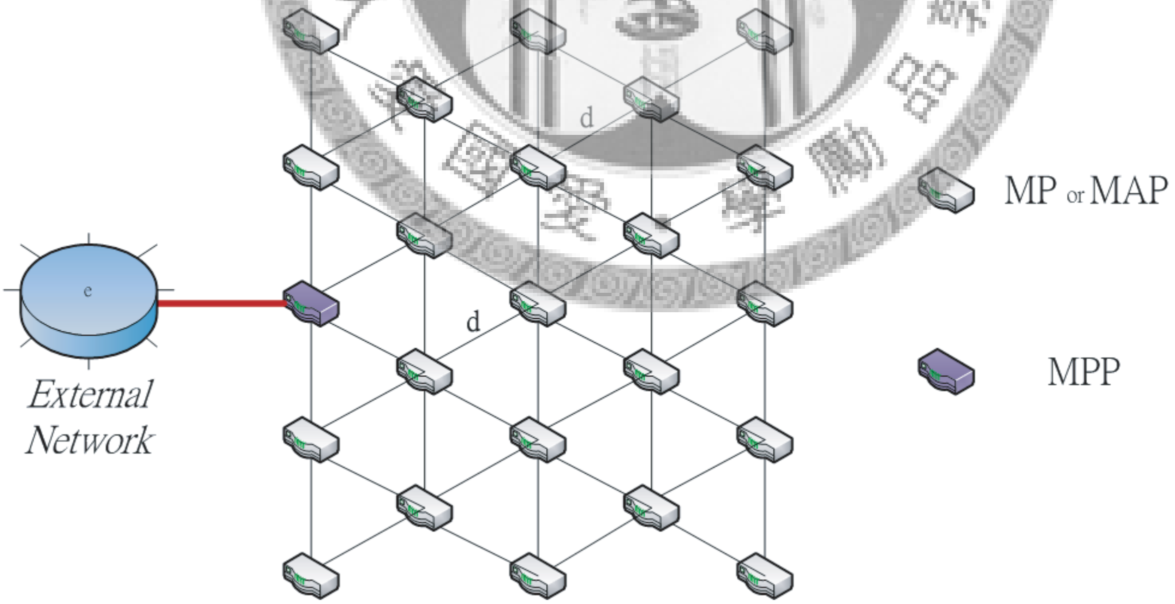

Figure 4.1: The simulation topology of a WMN.

Chapter 5

Simulation Results

5.1 Single Transmission Link with the Fixed Distance

Table 5.1: The throughput of each algorithms in Fig.5.1, Fig.5.2, Fig.5.5, and Fig.5.7

Algorithms	(1)	(2)	(3)	(4)	(5)	(6)
AARF	3.81 Mbps	0.73 Mbps	0.97 Mbps	0.85 Mbps	0.83 Mbps	0.39 Mbps
CARA	3.69 Mbps	0.75 Mbps	0.89 Mbps	0.56 Mbps	0.35 Mbps	0.23 Mbps
RRAA	2.53 Mbps	1.48 Mbps	0.29 Mbps	2.51 Mbps	0.29 Mbps	0.07 Mbps
SampleRate	3.85 Mbps	1.06 Mbps	5.24 Mbps	3.23 Mbps	0.25 Mbps	0.14 Mbps
Proposed	3.86 Mbps	1.39 Mbps	5.80 Mbps	4.04 Mbps	2.04 Mbps	0.78 Mbps
SARA	3.07 Mbps	1.18 Mbps	3.84 Mbps	2.27 Mbps	0.30 Mbps	0.20 Mbps
SLA	2.93 Mbps	1.17 Mbps	3.77 Mbps	2.26 Mbps	0.30 Mbps	0.20 Mbps

a. (1) (2) is the throughput of Fig.5.1 and Fig.5.2.
b. (4) is the throughput of Fig.5.4 with 15 nodes and (3) is (4) without Ricean fading.
c. (6) is the throughput of Fig.5.6 with 15 nodes and (5) is (6) without Rayleigh fading.

In this scenario, two stations are placed with the distance of 280 meters. In this situation, the rate 5.5 Mbps is the best choice. In this experiment, we want to investigate the rates chosen by different algorithms when only the large scale

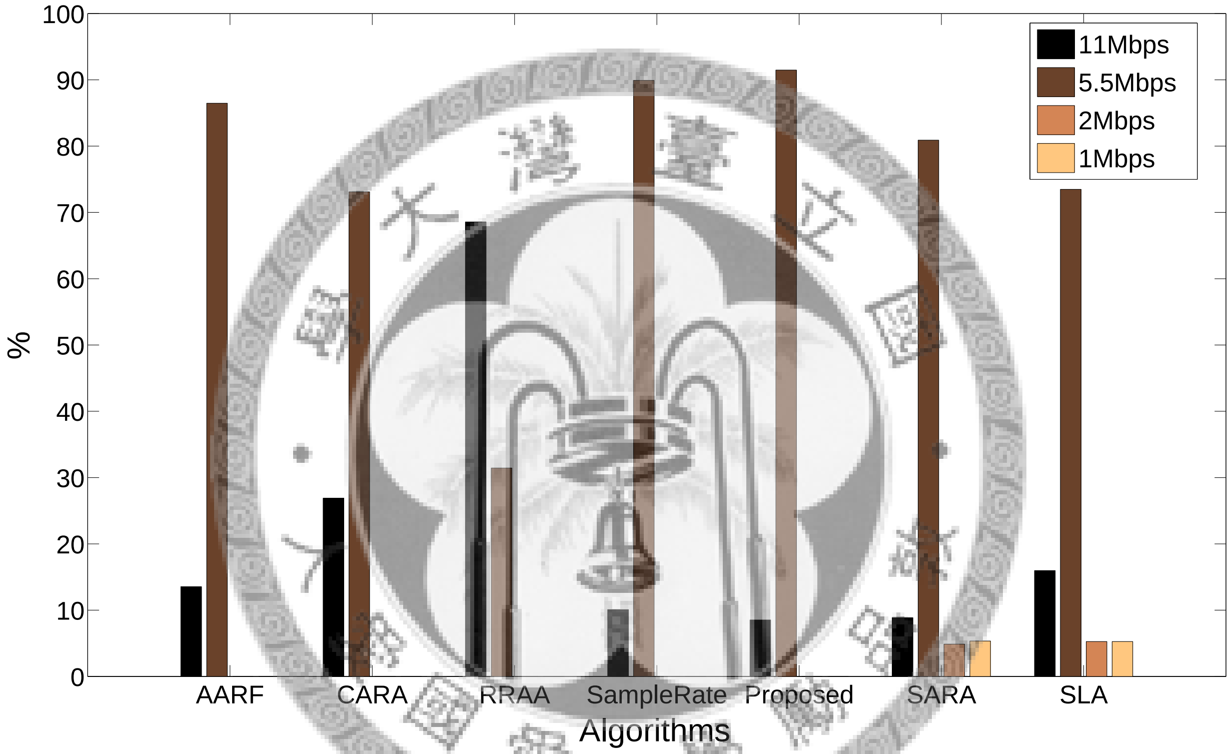

Figure 5.1: The percentage of every rate chosen by algorithms without small scale fading.

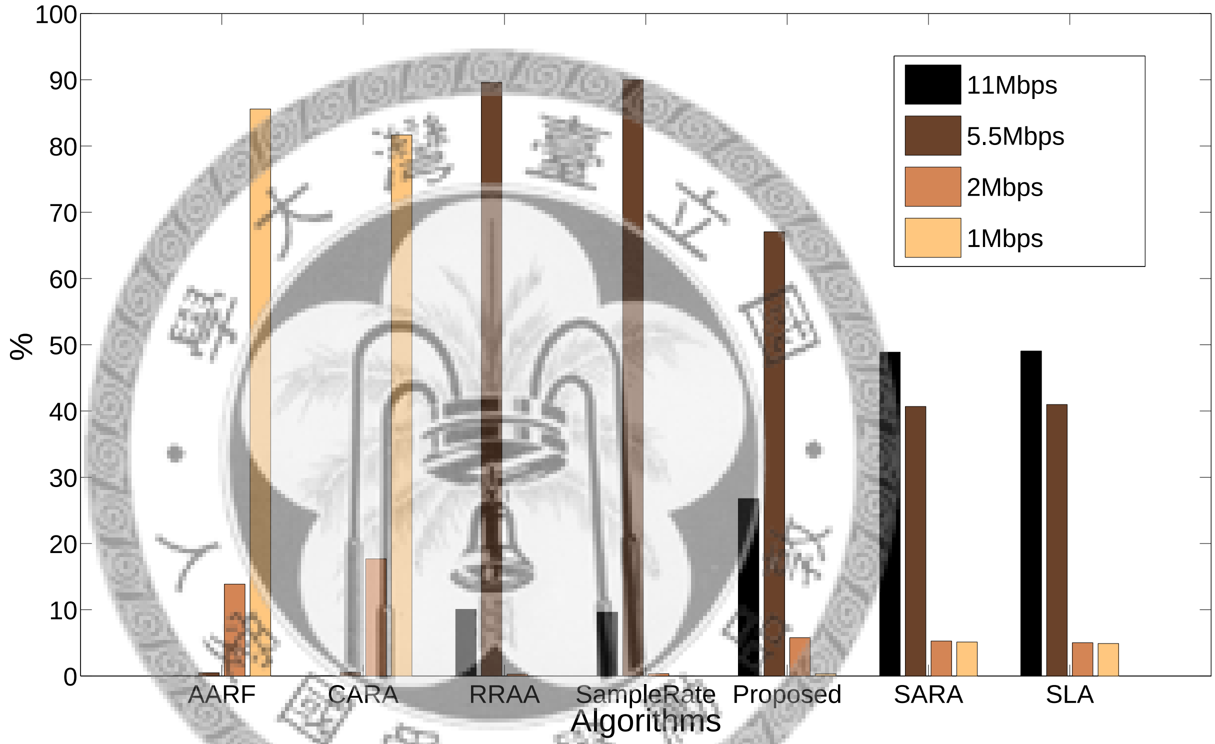

Figure 5.2: The percentage of every rate chosen by algorithms with Rayleigh fading.

fading, without the small scale fading, is used. Fig.5.1 shows the result of the percentage. It can be observed that the proposed algorithm and SampleRate can select 5.5 Mbps above 90%, and the proposed algorithm is even a little higher than SampleRate. SARA and SLA use stochastic automata, so both of them rarely choose 2Mbps and 1Mbps. One thing worth mentioning is that the rate chosen by RRAA would oscillate between 5.5 Mbps and 11 Mbps and that is the reason why RRAA has large percentage to choose 11 Mbps. This phenomenon is consistent with the problem of ping-pong effect for RRAA as reported in the literature [19].

Then the channel, not only the large scale fading but also Rayleigh fading, is considered. The purpose is to evaluate the decision flexibility and responsiveness of various algorithms to explore the short term characteristics of channel dynamics. Because the channel is varying dramatically with Rayleigh fading, the rate of 5.5 Mbps is not always the best choice at some time. When the channel is getting better, 11 Mbps would become the best choice. While the channel is getting worse, transmissions may be failed with the rate 5.5Mbps. From Fig.5.2, we can see that this time the proposed algorithm doesn't choose the rate of 5.5 Mbps with a high percentage, but SampleRate still selects 5.5 Mbps for almost 90%. When the channel is better, the proposed algorithm would choose 11 Mbps, and select 2 Mbps or 1 Mbps instead while the channel is bad. This can explain why, in Fig.5.3, it shows that the performance the proposed algorithm does actually better than SampleRate does. AARF and CARA take 1Mbps for most of the time because it is difficult for their mechanism to select a high data rate in a noisy environment.

5.2 Single Transmission Link with Different Distances

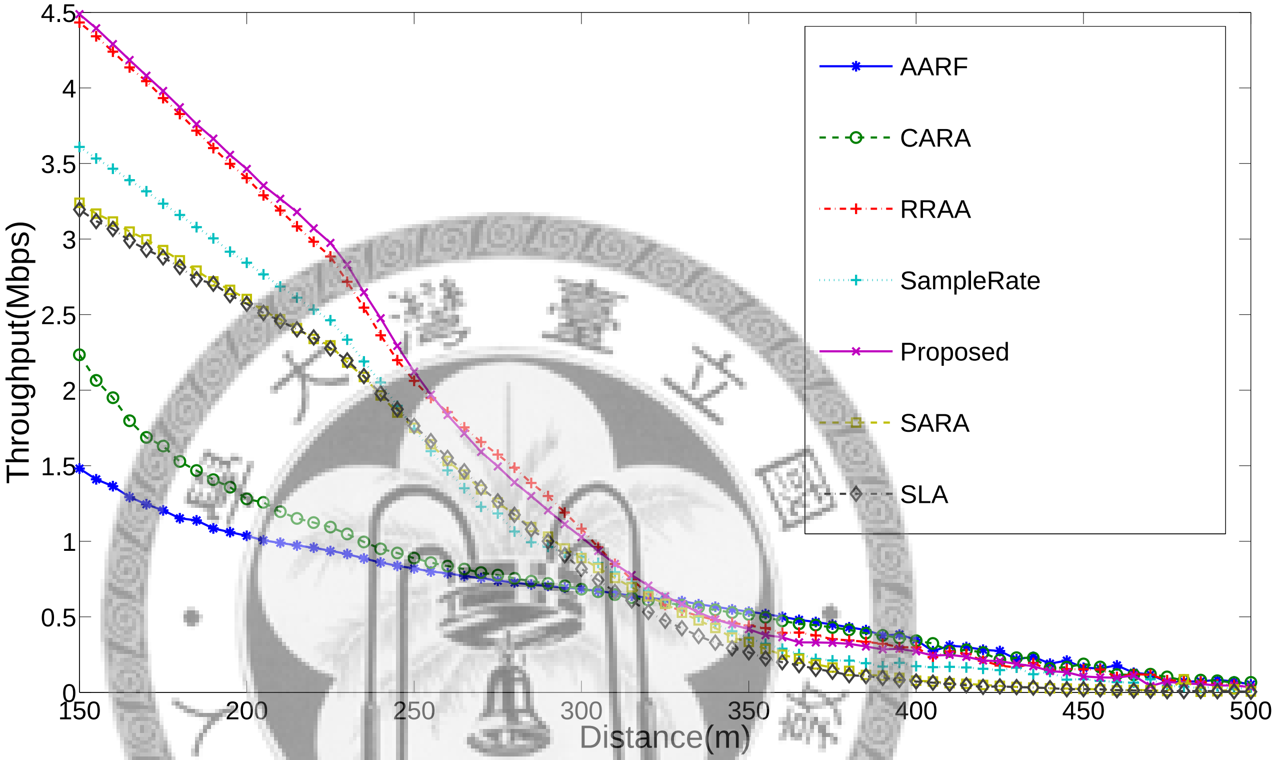

Figure 5.3: Throughput in different distance in Rayleigh fading.

In this scenario, two static stations are placed with different distances, from 150m to 500m, and Rayleigh small-scale fading model is assumed. Fig.5.3 demonstrates the throughput performance. In general, the throughput of every rate adaptive algorithm decreases as the distance increases . Among existing algorithms, RRAA performs the best. Similar observations has been reported [9]. We observe that the proposed algorithm performs almost the same as RRAA does in this scenario, better than SampleRate does. Because Rayleigh fading is a violent dynamic model, the timely and robust statistics is necessary in order to make the decision of choosing the appropriate MCS promptly in such channel conditions. The proposed algorithm exhibits such a characteristic and this is why it always produces better performance than others when the distance is below 330m. AARF and CARA are little higher than the proposed algorithm and RRAA when the distance is longer than 330m. 1 Mbps may be the best choice when the distance gets longer and longer; when the distance is longer than 330m, 1 Mbps would become the only possible choice to make a successful transmission. AARF and CARA choose the rate of 1 Mbps because they require consecutive successful transmissions in order to choose the higher data rate. The proposed algorithm and RRAA would choose the rates other than 1 Mbps in some cases, not doing as good as AARF or CARA does.

5.3 Multiple Static Stations in an Infrastructure Mode

In the experiment, we study the performance of different rate adaptive algorithms in an extensive contention environment with error-prone fading channels. Access Point (AP) stays statically in the center and we place a number of contending hosts around AP with the same radius. Experiments are performed with two distances (200m and 300m) and different fading channels. Fig.5.4 presents the aggregate throughput performances with respect to different numbers of hosts at the distance of 200m with the small-scale Ricean fading model. It should be noticed that the best MCS should be 11Mbps at this distance. It can be observed that the proposed algorithm, RRAA, and SampleRate produce comparable results when the number of contending hosts is small (less than 8). When the number

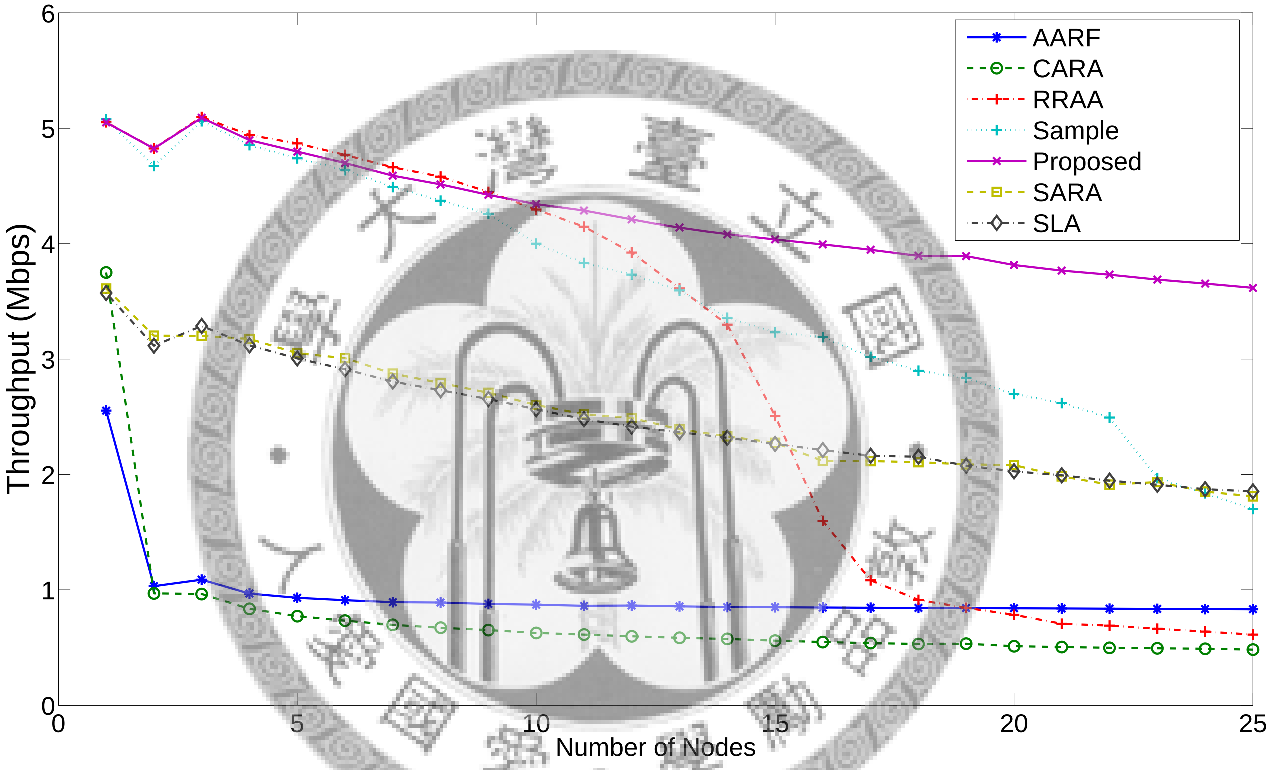

Figure 5.4: Multiple nodes vs. throughput in Ricean fading with distance = 200m

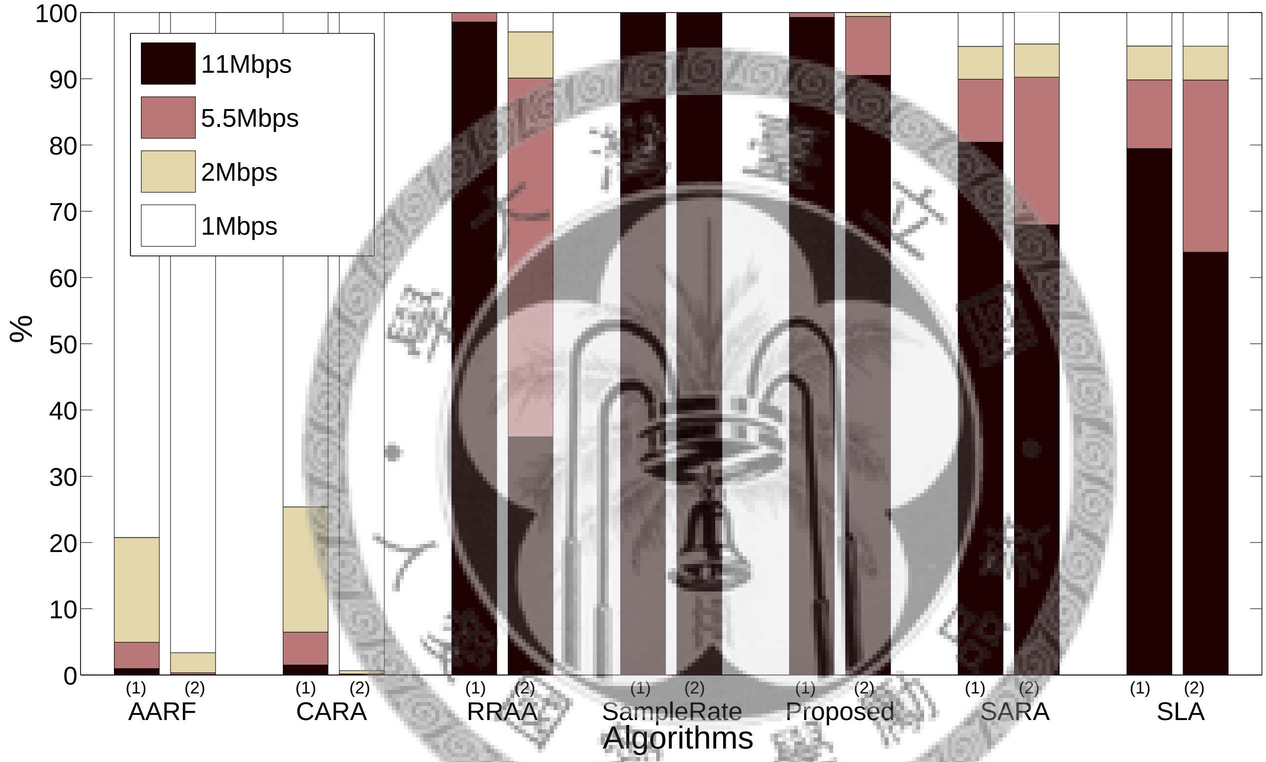

Figure 5.5: The percentage of rate selection of each algorithms with 15 stations in fig.5.4. (1) is no small scale fading and (2) is with Ricean fading.

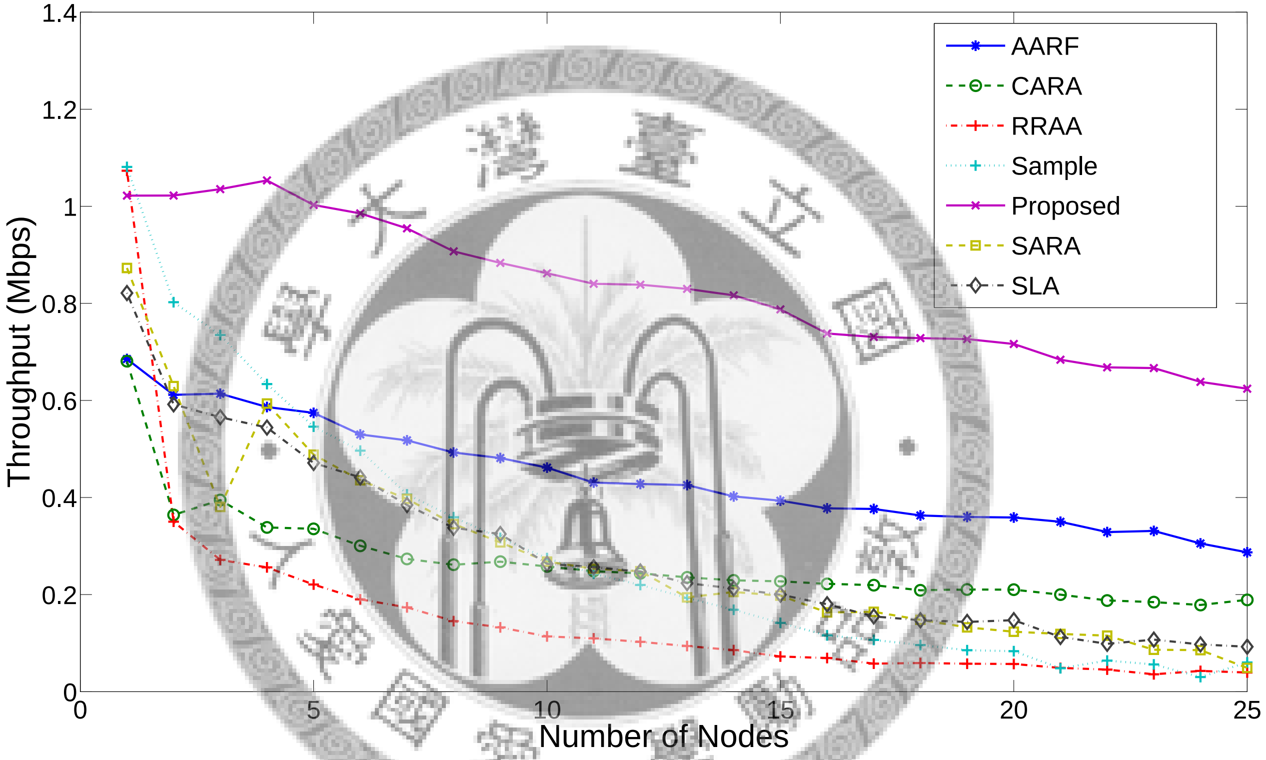

Figure 5.6: Multiple nodes vs. throughput in Rayleigh fading with distance = 300m.

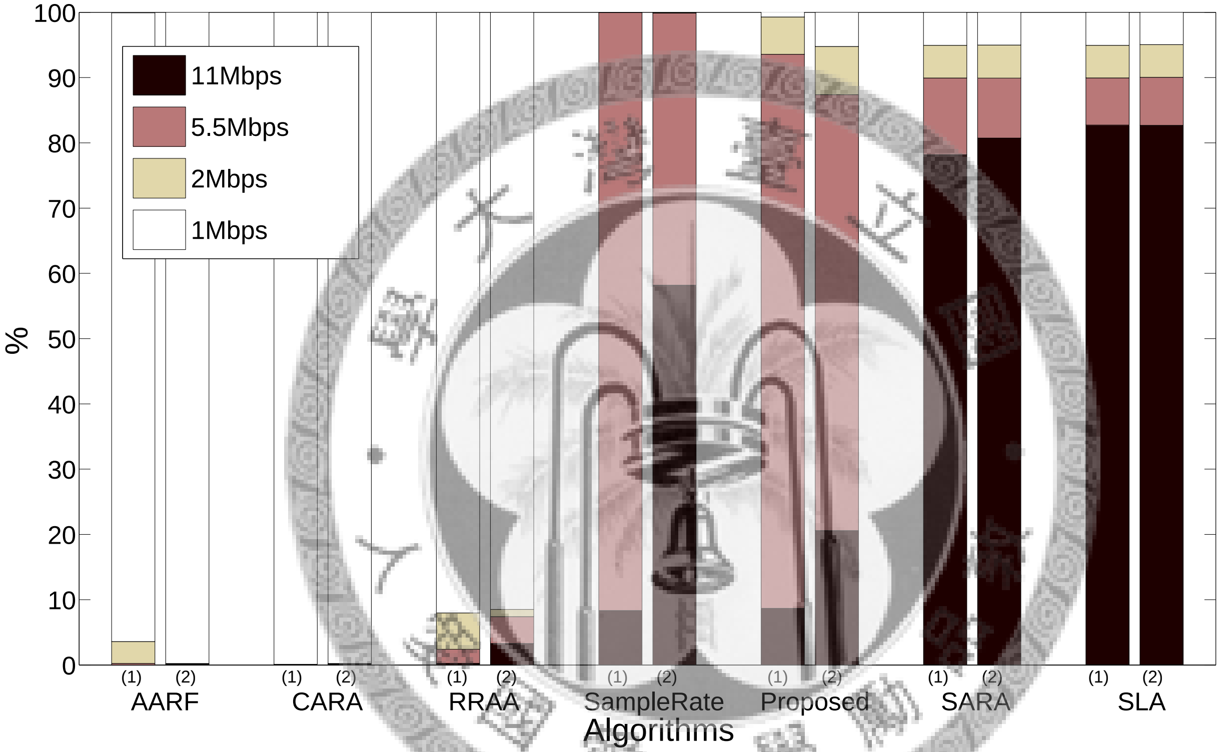

Figure 5.7: The percentage of chosen rates in an environment of 15 contending stations in Fig.5.6. (1) is no small scale fading and (2) is with Rayleigh fading.

of contending hosts is large, RRAA breaks down quickly. The original paper of RRAA [9] also reports the weakness of the design. To further investigate the detailed behavior, we plot the percentage of the rate selection for every algorithm with 15 stations in Fig.5.4 experiment. The results are shown in Fig. 5.5. There are two bars for each algorithm. The left bar is the experimental result when only the large-scale fading is assumed, and is displayed for the purpose of comparison. In only large scale fading channels, RRAA, SampleRate, and the proposed can easily make the correct decision (11Mbps). When the small-scale Ricean fading is applied, RRAA makes lots of wrong decisions and SampleRate can not make the flexible decision promptly. On the other hand, the proposed algorithm can well exploit the short-term characteristics of channel dynamics. Fig.5.6 displays the performance results when the distance becomes 300m and Rayleigh fading model is used. At this distance, the best MCS should be 5Mbps. The percentage results for both large-scale fading channels and Rayleigh channels are plotted in Fig. 5.7.

5.4 Multiple Mobile Stations in an Infrastructure Mode

In this scenario, an 800m*800m area is created, AP is statically placed in the center, and the small scale fading model is Rayleigh. Twenty stations are randomly placed in the area, and they move randomly at speeds from 1m/s to 10m/s. We generate the same traffic, saturated CBR traffic, from each station to AP. Small-scale Rayleigh fading channels are used in the experiment. The aggregate throughputs of different algorithms are shown in Fig.5.8. And the Fig.5.9 shows

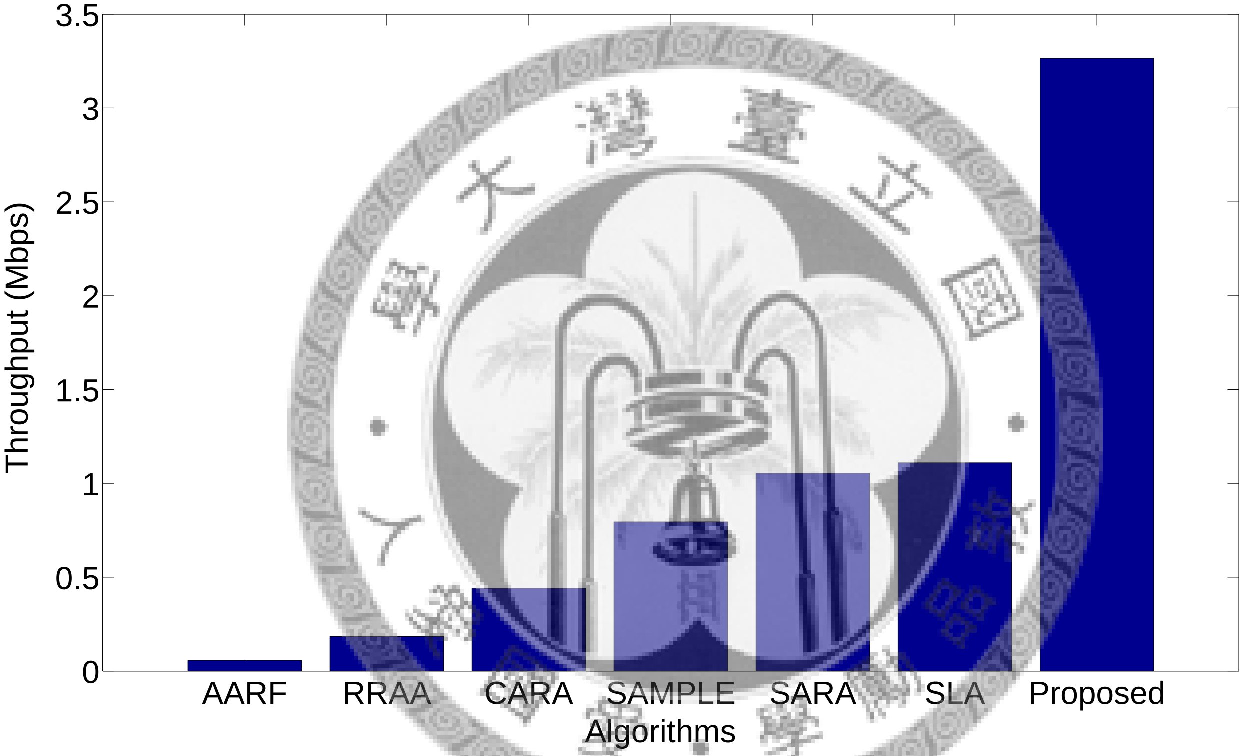

Figure 5.8: The aggregate throughputs for different rate adaptation algorithms.

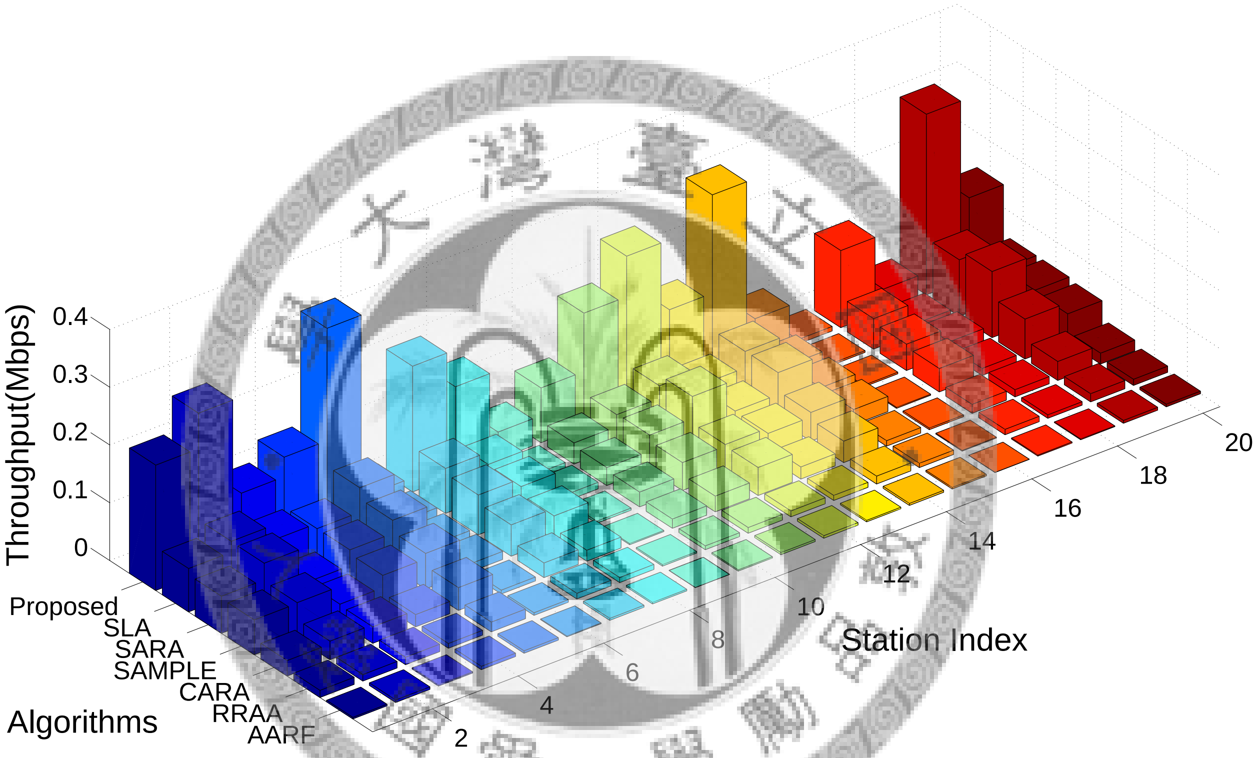

Figure 5.9: The individual throughput in every node for different rate adaptation algorithms

the throughput of each node. We observe that our mechanism can achieve the performance gain over the others more than 200%.

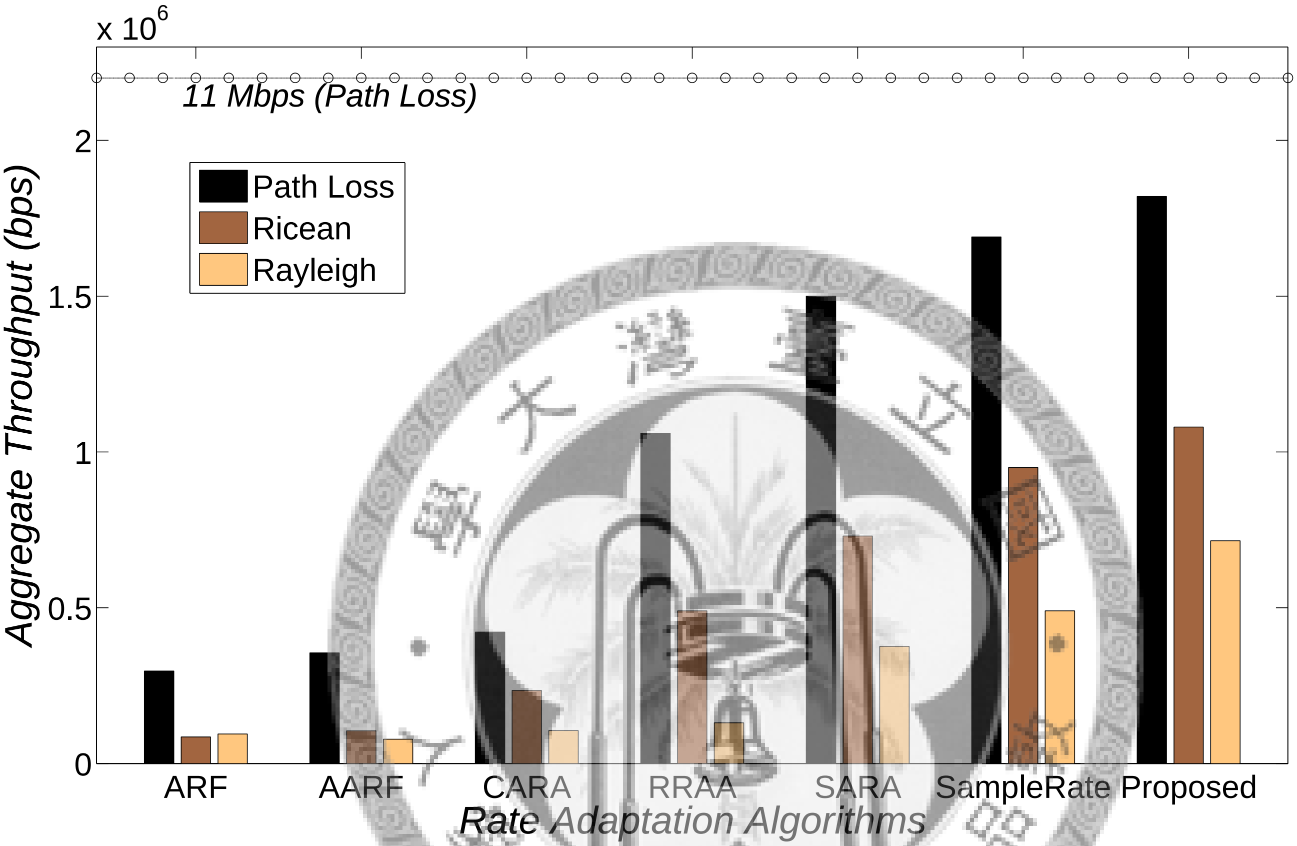

Figure 5.10: The aggregate throughput of each algorithm in the distance of 250 meters.

5.5 Topologies of Equal Distances

In the experiments, we compare the performances in two topologies of equal distances (250 meters and 370 meters). Fig. 5.10 and Fig. 5.12 show the aggregate throughputs respectively with different rate adaptation algorithms, in which ”Path loss” means two-ray ground reflection in the channel condition (large scale

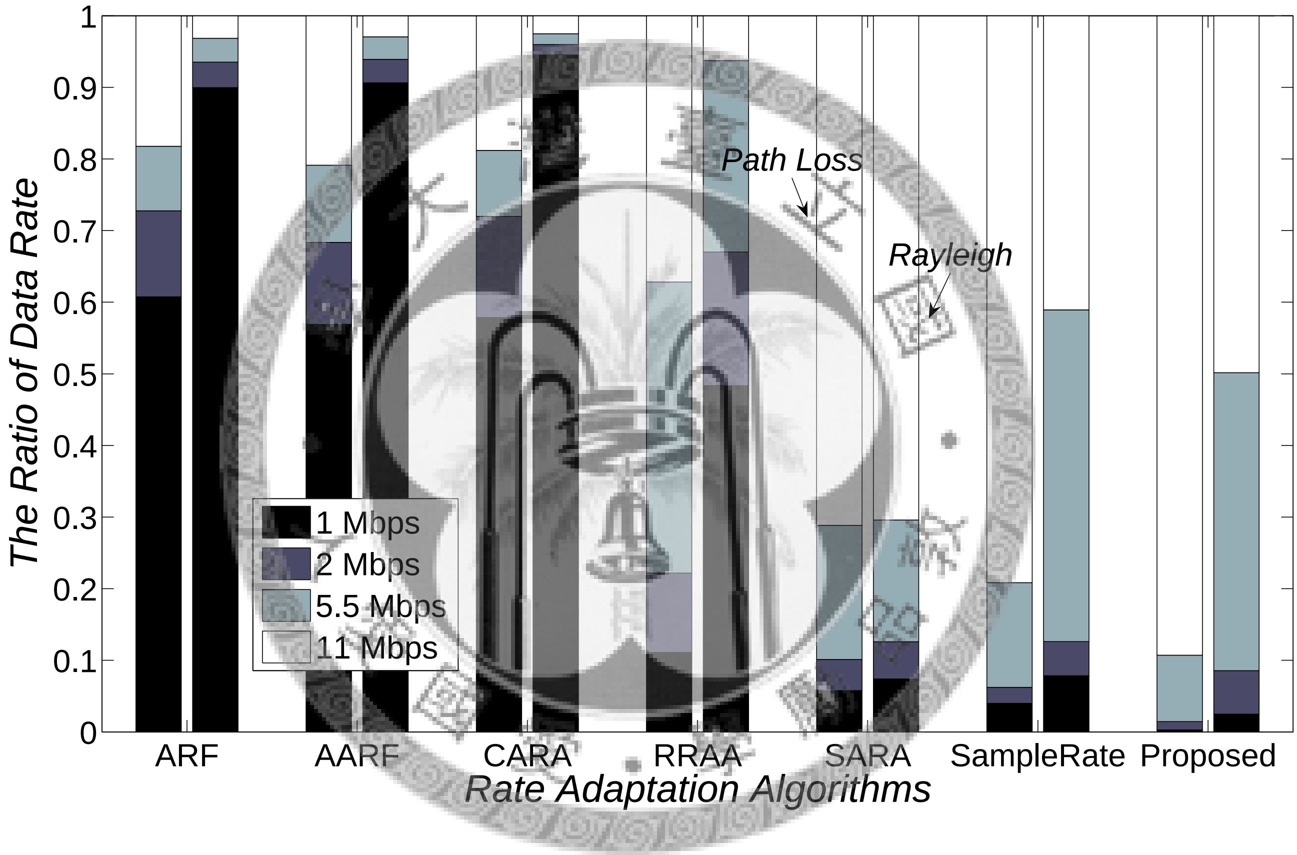

Figure 5.11: The ratio of data rate in the distance of 250 meters.

fading) is adopted and the line acroses the graph means the performance of the best fixed-rate for the comparison purpose.

Both results show the performances of all algorithms degrade when the channel fluctuations become severe. ARF-based algorithms use consecutive transmission success or failure to determine the rate. From both results, it can be observed the performances of such algorithms do not perform well since the characteristics of such a design make it difficult to choose the correct rate in a wireless mesh environment. Those algorithms attribute all transmission failures to corruption from error-prone channels. Therefore those algorithms are likely to incorrectly choose the rate in a wireless mesh environment where the collision may occur frequently. This phenomenon can be better explained in Fig. 5.11 and Fig. 5.13. The figures show the percentage of chosen data rates during the experiments. For the purpose of clarity, we only plot the results of two fading models of ”Path loss” (more stable) and ”Raleigh” (more random fluctuations). From Fig. 5.11, the percentage of 11 Mbps is low even in a stable channel condition. Although RRAA [9] is reported to be the best rate adaptive algorithm in the literature and the authors ”believe the proposed algorithm to perform well in 802.11-based wireless mesh networks”, our experimental results show an important observation that the performance of RRAA suffers in all channel conditions in a mesh environment. As [9] indicates that, when the channel condition becomes worse (i.e. SNR is low or contention level is high), RRAA can not deal with collision problem, the phenomenon can be easily observed from Fig. 5.12. In such a harsh environment, ARF-like algorithms even perform better than RRAA. From the rate-percentage results of Fig. 5.11 and Fig. 5.13 , the likelihood of chosen the correct data rate is not high in ”Path loss” channel model. One of the reasons can be attributed to that RRAA sets the threshold of each data rate in advance, then calculate MTL and ORI according to the estimation window [9] of each data rate. The determined threshold does not show enough flexility to sudden changes in channel conditions during the multi-hop transmission.

SARA reports better performance than RRAA in both distances. However, the rate-percentage results (Fig. 5.11 and Fig. 5.13) for "Path loss" and "Rayleigh" is almost identical. This analysis demonstrates SARA lack the responsiveness to the channel fading. Therefore, such a characteristics results in the performance degradation as observed in Fig. 5.10 and Fig. 5.12.

SampleRate and the proposed algorithm demonstrate the robust performance for all channel conditions in both topologies. The capability of chosen the correct rate rate can be easily shown from Fig. 5.11 and Fig. 5.13 in "Path loss" channel model. This explains why the proposed algorithm outperforms all existing well-known algorithms. From the results of fading channel models, they further demonstrate the proposed algorithm exhibits superior responsiveness compared to other algorithms and can better exploit the short-term channel variations. That is the reason why the proposed mechanism shows the best throughput performance as shown in Fig. 5.10 and Fig. 5.12.

5.6 Topology of Mixed Distances

In this experiment, the distances between stations are mixed with 250 meters and 370 meters in order to create a heterogeneous environment. Fig. 5.14 shows the aggregate throughput with different fading models. The best fixed-rate is 11 Mbps and is plotted for a reference. Fig. 5.15 shows the percentage

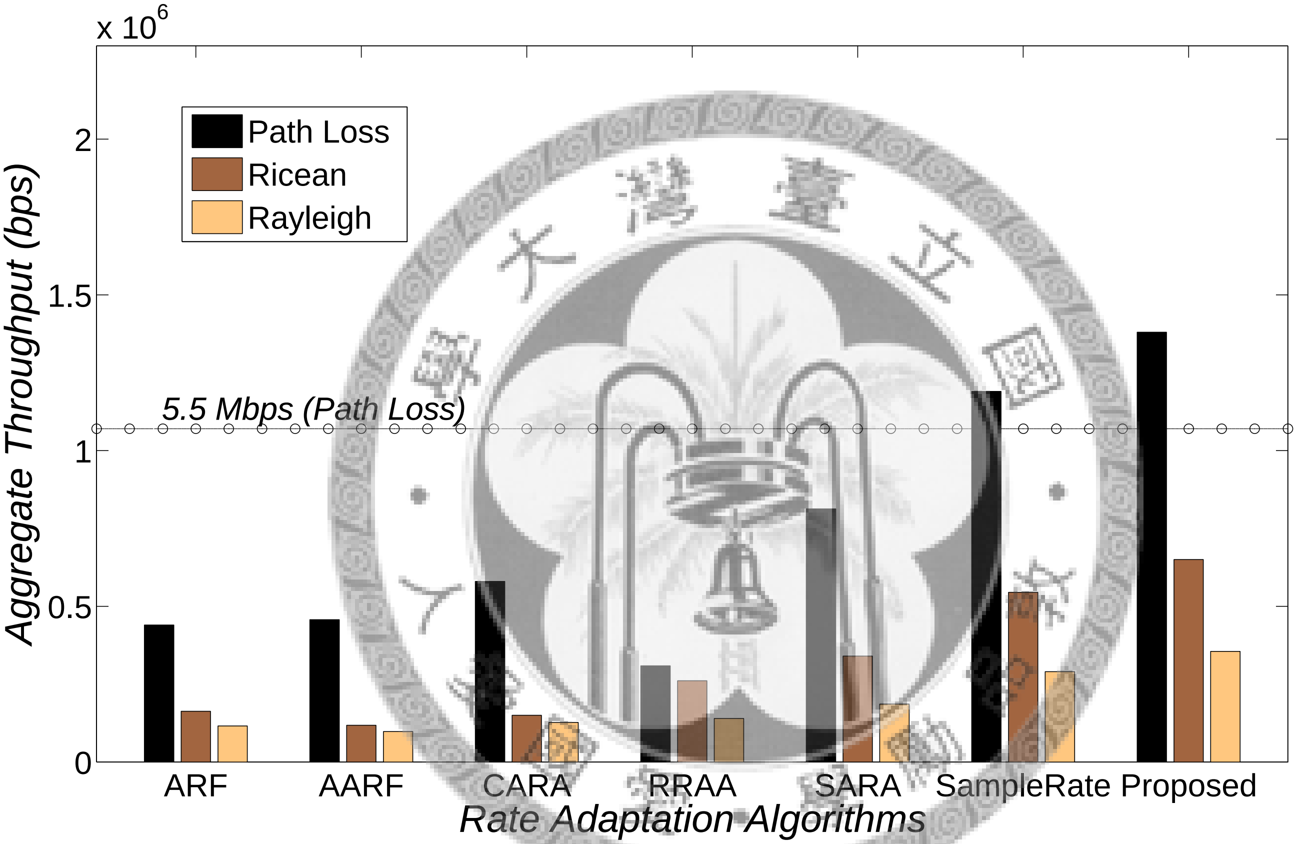

Figure 5.12: The aggregate throughput of each algorithm in the distance of 370 meters.

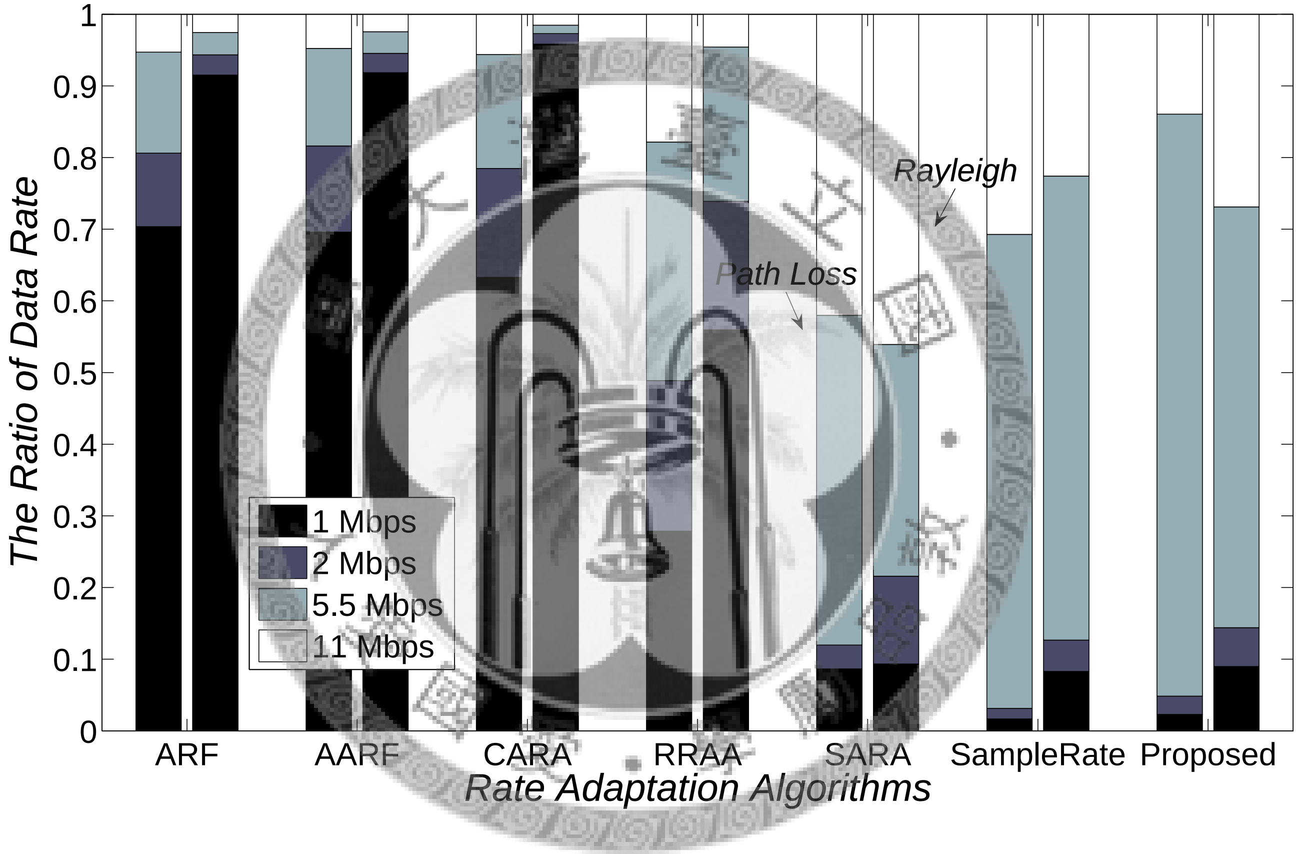

Figure 5.13: The ratio of data rates in the distance of 370 meters.

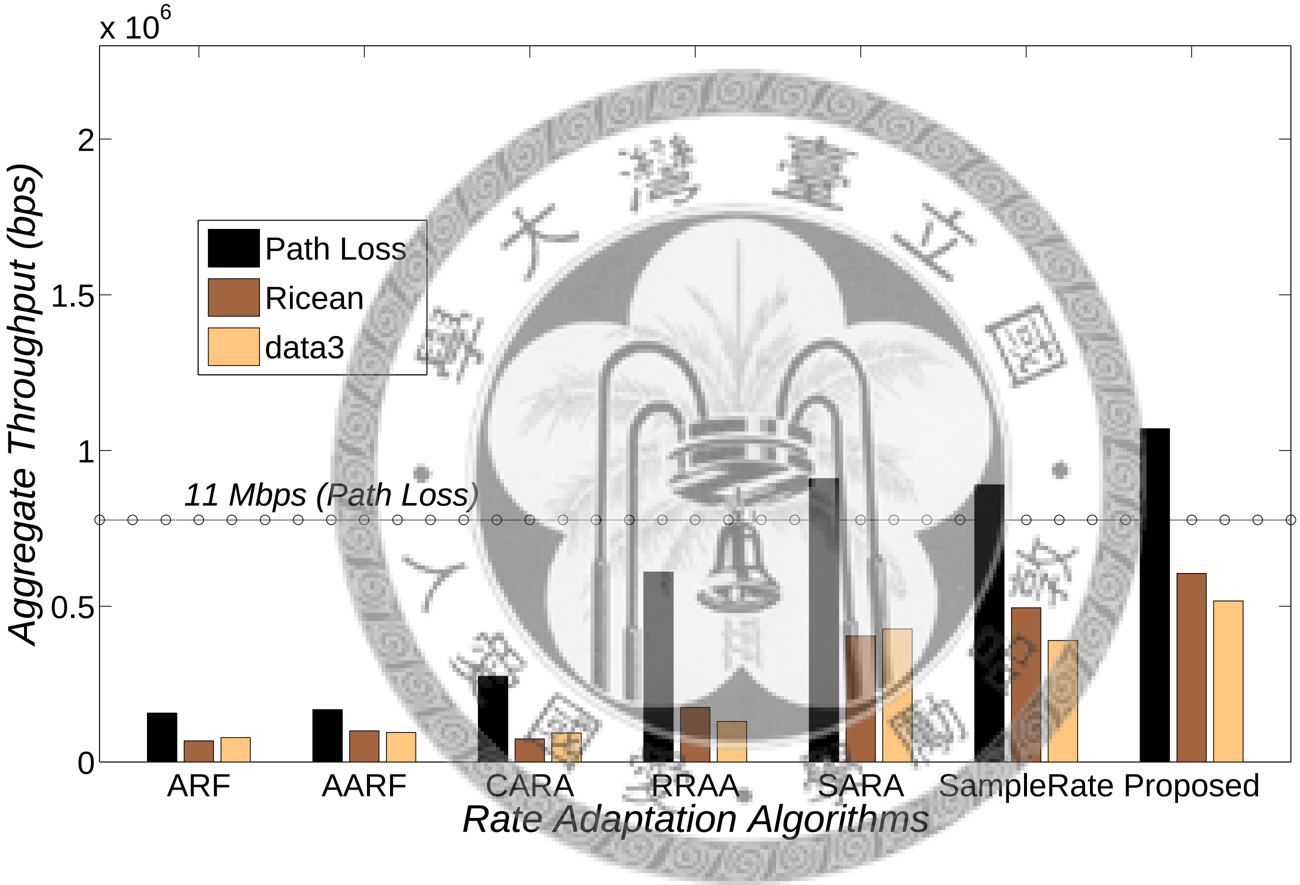

Figure 5.14: The aggregate throughput in the mixed type scenario.

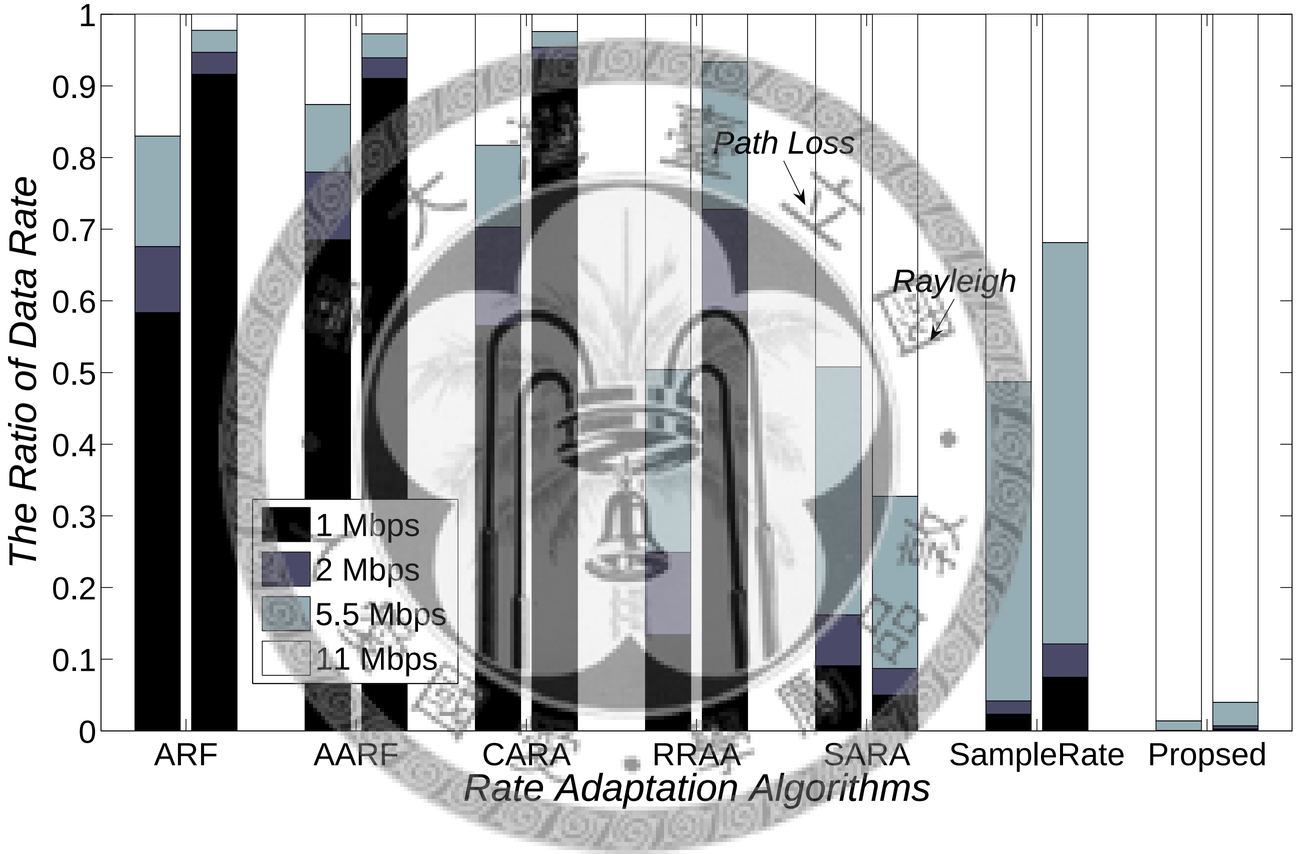

Figure 5.15: The ratio of data rates in in the mixed type scenario.

Chapter 6

Conclusions

In this paper, we study the rate adaption problem in IEEE 802.11 wireless networks and evaluate the performance of rate adaptive algorithms in 802.11-based wireless mesh network environments. The crux of the problem is to determine the state of the communication channels correctly and make the decision promptly. We propose a novel cross-layer approach to tackle via a machine learning approach. Maximum likelihood estimator is utilized to robustly estimate the channel state. Then the joint correlation between PHY and MAC is exploited in order to evaluate the performances of available MCSs. Our decision strategy is to achieve the maximum spectral efficiency. We evaluate the performances of the proposed approach as well as several existing algorithms through extensive simulations. The scenarios we consider include different topologies, fading channels, mobility, and various contending nodes. Experimental results show the proposed algorithm outperforms exiting algorithms in all scenarios and various wireless mesh network topologies.

Bibliography

[1] "IEEE standard for information technology-telecommunications and information exchange between systems-local and metropolitan area networks-specific requirements - part 11: Wireless lan medium access control (mac) and physical layer (phy) specifications," *IEEE Std 802.11-2007 (Revision of IEEE Std 802.11-1999)*, pp. C1–1184, 12 2007.

[2] J. Camp and E. Knightly, "The IEEE 802.11s extended service set mesh networking standard," *Communications Magazine, IEEE*, vol. 46, no. 8, pp. 120–126, August 2008.

[3] D. Johnson, "Routing in ad hoc networks of mobile hosts," *Mobile Computing Systems and Applications, 1994. Proceedings., Workshop on*, pp. 158–163, Dec 1994.

[4] "Optimized link state routing protocol (olsr)," 2003.

[5] C. Perkins and E. Royer, "Ad-hoc on-demand distance vector routing," *Mobile Computing Systems and Applications, 1999. Proceedings. WMCSA '99. Second IEEE Workshop on*, pp. 90–100, Feb 1999.

[6] G. B.-S. A. D. Martin Heusse, Franck Rousseau, "Performance anomaly of 802.11b," *IEEE INFOCOM*, 2003.

[7] G. Holland, N. Vaidya, and P. Bahl, "A rate-adaptive mac protocol for multi-hop wireless networks," in *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking.* New York, NY, USA: ACM, 2001, pp. 236–251.

[8] A. Kamerman and L. Monteban, "Wavelan-ii: a high-performance wireless lan for the unlicensed band," *Bell Labs Technical Journal*, vol. 2, no. 3, pp. 118–133, 1997. [Online]. Available: http://dx.doi.org/10.1002/bltj.2069

[9] S. H. Y. Wong, H. Yang, S. Lu, and V. Bharghavan, "Robust rate adaptation for 802.11 wireless networks," in *MobiCom '06: Proceedings of the 12th annual international conference on Mobile computing and networking*. New York, NY, USA: ACM, 2006, pp. 146–157.

[10] D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," *SIGCOMM Comput. Commun. Rev.*, vol. 34, no. 4, pp. 121–132, 2004.

[11] J. C. Bicket, "Bit-rate selection in wireless networks," Master's thesis, Department of EECS, MIT, February 2005, sampleRate.

[12] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: a practical approach," in *MSWiM '04: Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*. New York, NY, USA: ACM, 2004, pp. 126–134.

[13] J. Kim, S. Kim, S. Choi, and D. Qiao, "CARA: Collision-aware rate adaptation for IEEE 802.11 WLANs," in *INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings*, Apr 2006, pp. 1–11.

[14] D. S. Trrun Joshi, Disha Ahuja and I. Dharma P. Agrawal, Fellow, "Sara: Stochastic automata rate adaptation for IEEE 802.11 networks," *IEEE TRANSACTIONS ON PARALLEL AND DISTRIBUTED SYSTEMS*, vol. 19, p. 11, 2008.

[15] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *Selected Areas in Communications, IEEE Journal on*, vol. 18, no. 3, pp. 535–547, Mar 2000.

[16] http://www.scalablenetworks.com/, "Qualnet network modeler and simulator."

[17] M. Haleem and R. Chandramouli, “Adaptive downlink scheduling and rate selection: a cross-layer design,” *Selected Areas in Communications, IEEE Journal on*, vol. 23, no. 6, pp. 1287–1297, June 2005.

[18] P. Chatzimisios, A. Boucouvalas, and V. Vitsas, “Ieee 802.11 packet delay-a finite retry limit analysis,” *Global Telecommunications Conference, 2003. GLOBECOM ’03. IEEE*, vol. 2, pp. 950–954 Vol.2, Dec. 2003.

[19] K. Ramachandran, R. Kokku, H. Zhang, and M. Gruteser, “Symphony: synchronous two-phase rate and power control in 802.11 wlans,” pp. 132–145, 2008.