THE IMPACT OF RTS/CTS EXCHANGE ON THE PERFORMANCE OF MULTI-RATE IEEE 802.11 WIRELESS NETWORKS

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Dedication

This thesis is dedicated to my parents.

They have supported me in my studies.

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Abstract

The RTS/CTS mechanism is an optional mechanism in DCF (Distributed Coordination Function) in IEEE 802.11 standard, which was designed to solve the hidden node problem. However, the RTS/CTS mechanism is turned off in most infrastructure-mode WLANs because the additional RTS/CTS frames exchange introduces transmission overhead. People commonly believe that the benefits of RTS/CTS might not be able to pay off the transmission overhead in 802.11 WLANs. While this is often true in 802.11 WLANs with a single transmission rate, this investigation led to an opposite conclusion for 802.11 WLANs when multiple transmission rates are exploited. A phenomenon called *rate avalanche* was found in the investigation if the RTS/CTS mechanism is turned off in a heavily-loaded 802.11 WLAN. Even if no hidden node is present, high collision rates not only lead to packet retransmissions but also drive the nodes to switch to lower data rates. The retransmissions and the longer time occupation caused by lower rates will increase the amount of channel contention, which yields more collisions. This vicious cycle could significantly degrade the performance of WLANs even though no hidden node problem is present.

The research found that the effect of rate avalanche could be ameliorated by simply turning on the RTS/CTS mechanism in most cases of the investigation. Various scenarios/conditions are examined in studying the impact on the network performance for RTS/CTS on and off respectively. The investigation provides some insights about the impact of RTS/CTS exchange on the performance of multi-rate 802.11 WLANs.

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Abbreviations and Acronyms

ACK	acknowledgment
AP	access point
ARF	auto rate fallback
BER	bit error rate
BPSK	binary phase-shift keying
BSS	basic service set
CROAR	congestion reactive opportunistic auto rate
CSMA/CA	carrier sense multiple access with collision avoidance
CTS	clear to send
CW	contention window
DCF	distributed coordination function
DIFS	distributed (coordination function) interframe space
DS	distributed system
ESS	extended service set
FER	frame error rate
MAC	medium access control
NAV	network allocation vector
OAR	opportunistic auto rate
OFDM	orthogonal frequency-division multiplexing
PCF	point coordination function
PHY	physical (layer)
PLCP	physical layer convergence protocol
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
RBAR	receiver-based auto rate
RTS	request to send
RWPM	random waypoint mobility
SIFS	short interframe space
SINR	signal to interference plus noise ratio
TCP	transmission control protocol
UDP	user datagram protocol
WLAN	wireless local area network

1. Introduction

Today, we are witnessing the rapid growth of Wireless Local Area Networks (WLANs), especially IEEE 802.11 based WLANs. A lot of research efforts have been spent on WLANs, and most of these have focused on physical layer, medium access control (MAC), or cross-layers to improve the efficiency of the network performance. Employing the rate adaptation mechanism in WLANs to adjust the transmission rate dynamically for adapting the link condition to improve the performance is one example of these efforts.

Nowadays, most wireless network standards support multi-rate mechanisms at the PHY layer. For example, 802.11g supports the data rate in 6, 9, 12, 18, 24, 36, 48, and 54 Mbps [15]. In WLANs, the link quality is time-varying, and it is not always optimal for transmitting packets at higher data rates. The link quality could be influenced by several factors, such as path loss, fading, and interference. The rate adaptation mechanism is the process of selecting the appropriate data rate that can match the channel condition to optimize the throughput in the IEEE 802.11 MAC. Several rate adaptation schemes [10], [9], [26], [5], [4], [8], [11], [18], [27], and [30] have been proposed. These rate adaptation schemes are roughly divided into two types: SINR (Signal to Interference plus Noise Ratio)-based (e.g. [9], [26], [5], and [30]) and statistics-based (e.g. [10], [4], [8], [11], [18], and [27]). The SINR-based approach usually has better performance than the statistic-based approach because the SINR-based approach can measure link condition both timely and accurately. Thus the selected rate could match the channel condition most appropriately. Although the SINR-based approach has better performance than the statistic-based approach, the SINR-based approach is more difficult to implement. On the contrary, the statistics-based approach is widely used in most 802.11 devices because of its simplicity. This reason made me to focus on the efforts for enhancing the present statistics-based approaches and keeping them compatible with current 802.11 WLANs devices.

During the study on the network performance of rate adaptation mechanisms, a phenomenon called rate avalanche was found when the RTS/CTS mechanism is disabled and the ARF (Auto Rate Fallback) is employed in a heavily-loaded multi-rate wireless network. The disabled RTS/CTS exchange causes a high collision rate, which not only leads to packet retransmissions but also makes the nodes switch to the lower-rate transmissions; leading to more retransmissions and longer channel occupation time. This makes more contentions and causes more collisions to happen. This vicious cycle will degrade the whole network performance even though there is not any hidden node problem (i.e. two nodes are out of the transmission range from each other, and both of them are sending data to the same node at the same time. A collision will happen, and both of these two nodes have to retransmit the data again.). What reasons cause this phenomenon? (1) Statistics-based rate-adaptation schemes, like ARF, are not able to recognize the packet losses from collisions or from link errors, and all packet losses are counted to reduce the transmission rate. The lower-rate transmissions will make the data transmission occupy the channel longer and cause more contentions in the network, and then more contentions cause more collisions which will reduce the transmission rates. This vicious cycle will degrade the whole network performance. (2) Even though there is only one node less involved in the rate reducing cycle, the performance of this node is still degraded to the same level as the rest of the nodes which transmit at lower rates. This is the so-called performance anomaly [7].

However, from the investigation the effect of rate avalanche could be effectively ameliorated through enabling the RTS/CTS mechanism. This discovery has motivated on investigation of the impact of the RTS/CTS exchange on the performance of multi-rate WLANs. It is a challenge to set up a complete analytical model to study the network performance because of the characteristics of the wireless network, like the complexity of time-varying channel conditions, node mobility, various traffic patterns, and the effects on the behavior of the ARF algorithm. On the other hand, it is very expensive to build a real test bed with a larger number of nodes (e.g. 60 nodes). Due to these reasons, conducting the study by using the Network Simulator (ns-2) [19] is a practical solution. However, the current version of ns-2 does not satisfy the requirements of experiments. Although ns-2 has the complete and accurate simulation for 802.11 MAC layer, the support of the PHY layer is not sufficient for this investigation. For example, the reception model of the current ns-2 is the threshold-based frame reception model, i.e. if the received power of a frame is larger than the receiving threshold, this frame is received; otherwise the frame is dropped. The threshold-based reception model is too simple, and this reception model is not sufficient to present the character of time-varying channel conditions and frame errors. A concrete and realistic PHY implementation is needed. I have made some significant modifications in MAC and PHY layers (based on the other implementation of ns-2 [1]) to facilitate the investigation. Beside the original support of multi-rate and ARF from [1], this implementation also has two features: (1) It has a realistic propagation model that is suitable for mobile networks in an urban area. (2) A

FER (Frame Error Rate)-based reception model is employed, which could represent the error performance of 802.11a PHY modulation techniques and coding schemes.

This investigation provides these conclusions about the impact of the RTS/CTS exchange in multi-rate 802.11 wireless networks:

- Turning off the RTS/CTS mechanism in heavily-loaded multi-rate 802.11 WLANs could degrade network performance, particularly if the rata avalanche effect is the major cause of performance degradation.
- The impact of the RTS/CTS exchange in lightly-loaded multi-rate 802.11 WLANs is negligible.
- TCP-based applications have less severe effect of rate avalanche than UDP-based applications because TCP-based applications have the ability of self-adaptation.
- With all factors considered, turning on the RTS/CTS mechanism will have a higher chance of getting better performance than disabling the RTS/CTS mechanism.
- If using a pre-configured RTS threshold to employ the dynamic RTS/CTS exchange, it will only lead to sub-optimal network performance. This is because the optimal RTS threshold depends on several factors such as the number of competing nodes, the geographic distribution of nodes and node mobility. However, all these factors vary in a real network.

2. Background and Related Work

2.1 IEEE 802.11 Network and MAC

The IEEE 802.11 standard is the specification for wireless local area networks (WLANs), and it has been widely adopted in most commercial WLAN products. The IEEE 802.11 standard defines the medium access control (MAC) and physical layer (PHY).

Two types of wireless services are defined in the 802.11 standard, namely BSS (Basic Service Set) and ESS (Extended Service Set). The BSS is made up of several fixed or mobile wireless stations and an optional central base station, known as the access point (AP). The BSS is a stand-alone network, and it cannot send any data to other BSSs. A BSS without an AP is called an ad-hoc network. In this mode, IEEE 802.11 stations have the ability to communicate with each other directly. On the other hand, a BSS with an AP is called an infrastructure network in which all the communication must go through the AP. The ESS is a large coverage network which is made up of several BSSs with APs. BSSs are connected to each other by APs through a distribution system (DS). The distribution system is an architectural component used to interconnect BSSs, and this system allows the wireless network to be extended using multiple access points without needing a wired backbone to connect them together.

The IEEE 802.11 defines two MAC access mechanisms: the distributed coordination function (DCF) and an optional point coordination function (PCF). The latter is a centralized MAC protocol that provides collision free and time bounded service. The DCF is the basic access method of the IEEE 802.11 MAC, and it is derived from carrier sense multiple access with collision avoidance (CSMA/CA). CSMA/CA is designed to

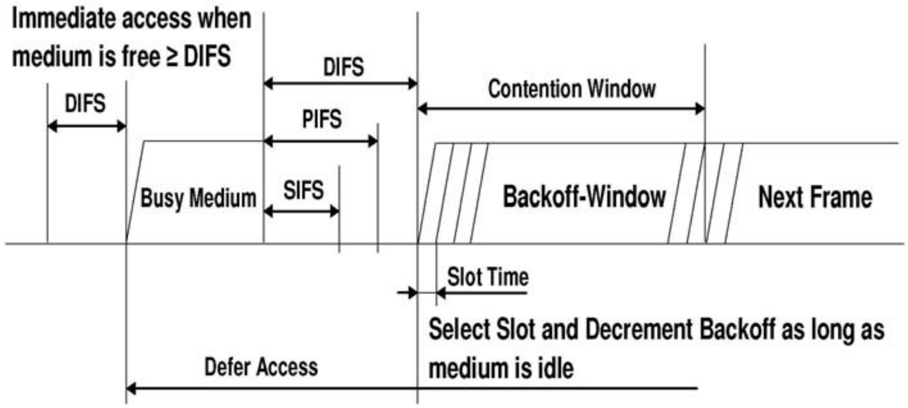


Figure 2.1 IEEE 802.11 DCF Basic Access Method

reduce the probability of collision, and all stations must follow two medium access rules: (1) In CSMA/CA protocol, a station has to sense the channel before starting its transmission to determine if another station is transmitting. This station also shall ensure the channel has been idle for a period of time called DCF Inter Frame Space (DIFS) and then the transmission is allowed. (2) The CSMA/CA mechanism defines a specified duration called a backoff timer between two consecutive frame transmissions from the same station. A backoff count value is picked randomly that is uniformly distributed between [0, CW-1] (CW – Contention Window), and the backoff timer is equal to the backoff value × a slot time (i.e. slot time = 9μs in 802.11a). The backoff timer decreases by a slot time every time the channel is determined to be idle. The backoff procedure is suspended when the channel is determined to be busy at any time during the backoff procedure and is allowed to resume when the channel is determined to be idle longer than DIFS. The transmission should be started when the backoff timer reaches zero. However, CSMA/CA cannot totally avoid collisions when two or more stations transmit at the same time. Therefore, these stations should have retransmissions and start the backoff procedure again. At this time, the CW value will be doubled. The CW value is limited in a range between the minimum (CWmin) and maximum (CWmax) values. Figure 2.1 demonstrates the IEEE 802.11 DCF access method.

2.2 RTS/CTS Mechanism

In DCF, the two-way handshaking technique is used as the basic access mechanism for packet transmission. However, it is not sufficient to handle all situations in a wireless network, such as the hidden node problem.

The hidden node problem happens in a wireless network when the stations are out of the range of the sending station but in the range of a receiving station. Figure 2.2 shows an example of the hidden node problem. The circles are the transmission range for each station, n_0, n_1, and n_2. Every station in the transmission range can hear any signal transmitted from the sending station. In Figure 2.2, n_0 and n_2 are out of the transmission range of each other, and they cannot hear each other. When n_0 is sending data to n_1, and during the transmission time, n_2 also has a data transmission to n_1. However, n_2 is out of n_0's transmission range and n_2 cannot receive any transmission from n_0. Then, n_2 thinks the channel is idle, and it starts a transmission to n_1. A collision will happen at n_1 because n_1 is receiving data from both n_0 and n_2 at the same time. In this situation, n_0 and n_2 are called "hidden nodes" from each other. Due to a collision, n_0 and n_2 need to retransmit the data packet. Therefore, the hidden node problem will reduce the capacity of the

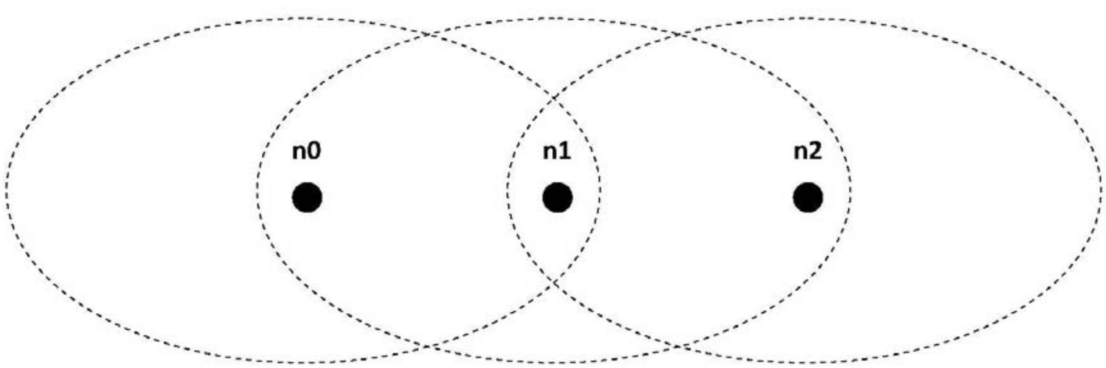


Figure 2.2 Hidden Node Problem

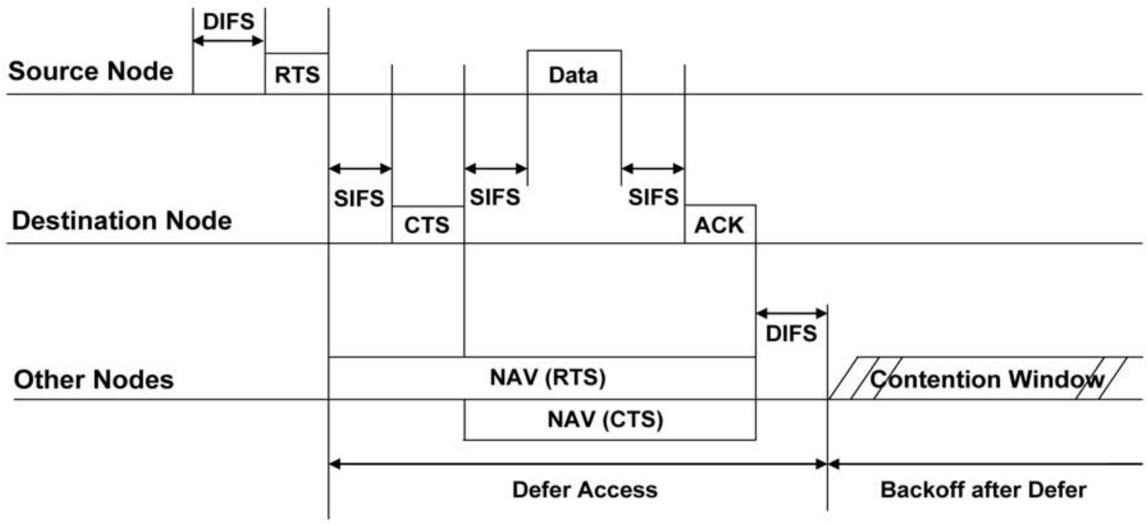


Figure 2.3 IEEE 802.11 RTS/CTS Exchange Scheme

network and degrade the network performance because of the high probability of a collision.

DCF defines an optional RTS/CTS mechanism which can reduce the probability of collisions caused by the hidden node problem. Figure 2.3 illustrates the RTS/CTS exchange scheme. The RTS/CTS mechanism is a four-way handshaking mechanism. A station needs to follow the medium access rules explained in 802.11 MAC layer when it has a packet to transmit. However, before sending a data packet, this station needs to send a special short frame which is called a Request-To-Send (RTS). When the destination station receives this RTS frame, it will send back a Clear-To-Send (CTS) frame after a short period of time (SIFS – Short Inter Frame Space). The sending station can only transmit this data packet after it receives the CTS frame correctly. The NAV (Network Allocation Vector) is the duration of time that predicts how long the medium will be occupied for the transmission. NAV is contained in the MAC header of the RTS/CTS frame. All stations (except the sender and the receiver) should update their NAV after receiving the RTS/CTS frames. These stations are not allowed to sense the medium status until their NAVs are expired. The following example explains the procedure of the RTS/CTS mechanism and presents how the RTS/CTS mechanism to solve the hidden node problem: n_0 will send a RTS frame before starting a transmission to n_1. Even though n_2 cannot hear this RTS frame, n_2 still can hear a CTS frame from n_1. This CTS frame contains the duration of the transmission from n_0 to n_1. n_2 knows the medium will be occupied by other stations, and n_2 will defer its transmission until the duration is over [12].

The RTS/CTS mechanism can effectively ameliorate the hidden node problem, but the RTS/CTS mechanism is not used for every data frame transmission because the RTS/CTS frame exchange will cause additional transmission overhead. The additional transmission overhead could be very significant for short data frames [12]. The IEEE 802.11 standard defines the size of RTS and CTS frames to be 20 and 14 octets respectively, and the RTS/CTS frame is transmitted at a low data rate (i.e. Basic Data Rate [12]). When the short data frames are transmitted with the RTS/CTS mechanism enabled, the performance of the network will be degraded because of the transmission overhead of the RTS/CTS frames exchanged. To mitigate the effect of the transmission overhead of RTS/CTS, IEEE 802.11 MAC protocol defines the RTS/CTS exchange as an optional mechanism. The use of the RTS/CTS mechanism is configured by the RTS threshold. If the length of the data frame is longer than the RTS threshold, the RTS/CTS mechanism will be turned on; otherwise, the RTS/CTS mechanism will be turned off. In most IEEE 802.11 WLANs, a large value is set as the RTS threshold (e.g., 3000 octets) to disable the RTS/CTS mechanism.

Beside the transmission overhead and its effectiveness to solve the hidden node problem, other possible effects of the RTS/CTS exchange have been rarely studied. [3] is an exception, and Bianchi pointed out that the RTS/CTS exchange might help to reduce the collisions to enhance the network performance in a heavily-contending WLAN environment even if no hidden node problem is present. However, Bianchi's analytical model assumed ideal channel conditions (i.e. error-free links) and only considered single-rate transmission.

Therefore, there is a lack of a thorough study on the effects of the RTS/CTS exchange on 802.11 WLANs, especially when using multi-rate transmissions and channel conditions that are time-varying and non-ideal.

2.3 Rate Adaptation

The wireless channel condition is time-varying and can be influenced by several factors, such as path loss, shadowing, multi-path fading, and interference. Usually, the wireless channel condition is indicated by the signal-interference-plus-noise ratio (SINR). The higher the SINR, the better the link channel condition is. The throughput of data transmissions over a wireless link is decided by the data rate, which is further decided by the modulation scheme used and the packet error rate (PER), which has a close relation to the SINR. A lower SINR usually causes a higher PER. So, for a specific channel condition (SINR), a higher data rate does not always lead to a higher throughput. Instead, an optimal data rate should be selected to match the channel condition (SINR). Many existing WLAN devices are designed with the capability to transmit at multiple rates. For example, IEEE 802.11 family defines multiple transmission rates at the PHY layer, like 802.11a supports eight rates (6~54 MBps) [13], 802.11b provides four rates (1~11 MBps) [14], and 802.11g supports twelve rates (1~54 MBps) [15]. An efficient rate-adaptation algorithm should be able to select an optimal transmission rate at a given time to match the channel condition (SINR). Figure 2.4 demonstrates the relation between the throughput and distance. [Note that in Figure 2.4, for simplicity, other factors that make the channel condition time-varying, such as shadowing, fading, and interference, are ignored.] Assuming that the transmission power is constant, the lower rate schemes have a greater transmission distance than the higher rate schemes.

The IEEE 802.11 standard does not specify about the rate-adaptation algorithm [8], and most wireless networking devices use the rate control algorithms which are designed and implemented by manufacturing companies. Choosing an optimal rate for the best throughput requires obtaining some information about the link condition, but measuring the link condition directly is very difficult. According to the method used to decide which optimal rate is selected at each specific moment, the auto rate control algorithms are divided into two types. One is the statistics-based approach, and the other one is SINR-based. The statistics-based approach is a way of collecting the information which is related to link condition directly. The information is like the FER (Frame Error Rate), ACK (Acknowledgment) packet transmission, or the archived throughput. According to the information, some statistics and estimates of the link condition can be done using the approximate statistics. The SINR-based approach is totally different than the statistics-based approach. The SINR-based approach is to measure link condition directly and switch to the rate which can perform the best throughput. In this way, two targets need to be achieved: (1) Building an accurate model that can present the relation between SINR and the optimal data rate for the network performance. (2) The sender must have the ability to estimate the precise SINR which is calculated at the receiver when the packet is received. Then, an optimal rate adaptation algorithm could be implemented simply by

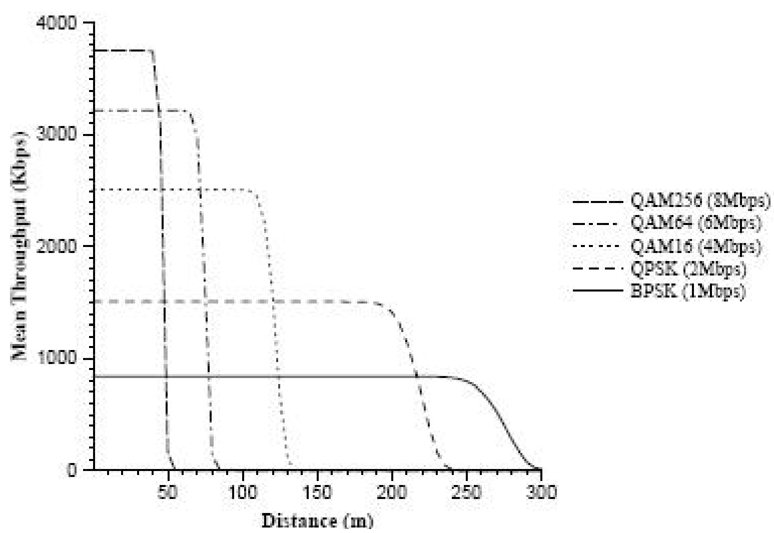


Figure 2.4 Comparison of Throughput versus Distance for Several Modulation Schemes

means of a lookup table for the SINR-based approach, but neither (1) nor (2) is easy to accomplish in reality. In the SINR-based approach, the SINR could reflect the link condition directly. Therefore, the sensitivity of changes to the link condition can be improved a lot. Because in the statistics-based approach, the condition is only in "good" or "bad", the link condition only can be measured roughly, which is not precise enough. According to the information which is provided by statistics-based feedback, it cannot pick up an appropriate rate right away. This means the data rate cannot respond to the link condition very quickly, especially for a large change in link condition during a short time. Despite the fact that the SINR-based approach has the advantage on quick response, it is a big challenge to estimate the time-varying link condition accurately. It is not like the statistics-based approach which is used in most of the 802.11 devices, and it is only used in academic research and simulations.

Auto Rate Fallback (ARF) protocol is built on the statistics-based approach and it was the first to be developed commercially. It is compatible with the existing 802.11 protocol and has been widely used in many network devices. Figure 2.5 shows the finite state machine of ARF. In ARF, if two consecutive ACKs are not received by the sender, the sender drops the transmission rate to the next lower rate and starts a timer. If the sender received ten consecutive ACKs, it raises the rate to the next higher rate and cancels the timer which it set previously. If the timer is expired, the sender raises the rate like before, but if ACK is not received for the varying next packet, the rate is lowered again and the timer is started. ARF has its own weakness, similar to what we mentioned previously about the statistics-based approach, which cannot adapt to the fast-changing link conditions. Even then ARF is still the most widely used rate adaptation algorithm in today's 802.11 networking devices.

On the other hand, several SINR-based approaches have also been proposed, such as RBAR [9], OAR [26], CROAR [30] and others [5], [17], [20]. Receiver-Based Auto Rate (RBAR) is a protocol which allows the receiver to select the appropriate rate for a data frame based on the RTS/CTS frame exchange, and it has both channel quality estimation and rate selection mechanisms on the receiver [9]. When the receiver receives the RTS frame, the receiver will analyze this received frame and then set the highest rate which can fit in the link condition to the next data transmission. The selected rate is more suitable for the actual link quality than the statistics-based approach. Despite this advantage, it is not used in practical devices because RBAR needs some minor changes to implement into IEEE 802.11, for example, RBAR needs to modify the frame format in MAC protocol for giving data rate to the sender.

Opportunistic Auto Rate (OAR) [26] was designed to exploit the duration when the channel link quality is good. The key mechanism of OAR is to send multiple packets back-to-back opportunistically whenever the link quality is good. By this method, stations will transmit more data packets than usual during the duration of a high-quality channel. OAR enhances the existing rate adaptations, and it can be applied to most rate adaptations, such as ARF and RBAR, to improve the throughput.

It is worthwhile noting that, although the rate-adaptation mechanism is designed to select an optimal transmission rate and maximize the flow throughput, it could degrade the performance of the whole network. In [7], some stations with lower data rates will degrade the performance of other station with higher transmission rates. This situation will happen, especially when a station is far away from the AP. The same issue was also addressed in [26] by Sadeghi et al, where it is pointed out that the throughput fairness in 802.11 multi-rate networks might make the whole network suffer performance degradation significantly; the authors thus proposed the time-share fairness to improve this problem. Since then, some research of time-share fairness has been proposed (e.g. [21], [28], [29]).

This investigation focuses on the statistic-based approach because all commercial 802.11 equipments use the statistic-based approach for rate control, and the ARF rate-adaptation algorithm is widely used in most 802.11 devices. Therefore, the ARF rate-adaptation algorithm is employed in all the simulations to keep the result of the investigation compatible with current 802.11 WLAN devices.

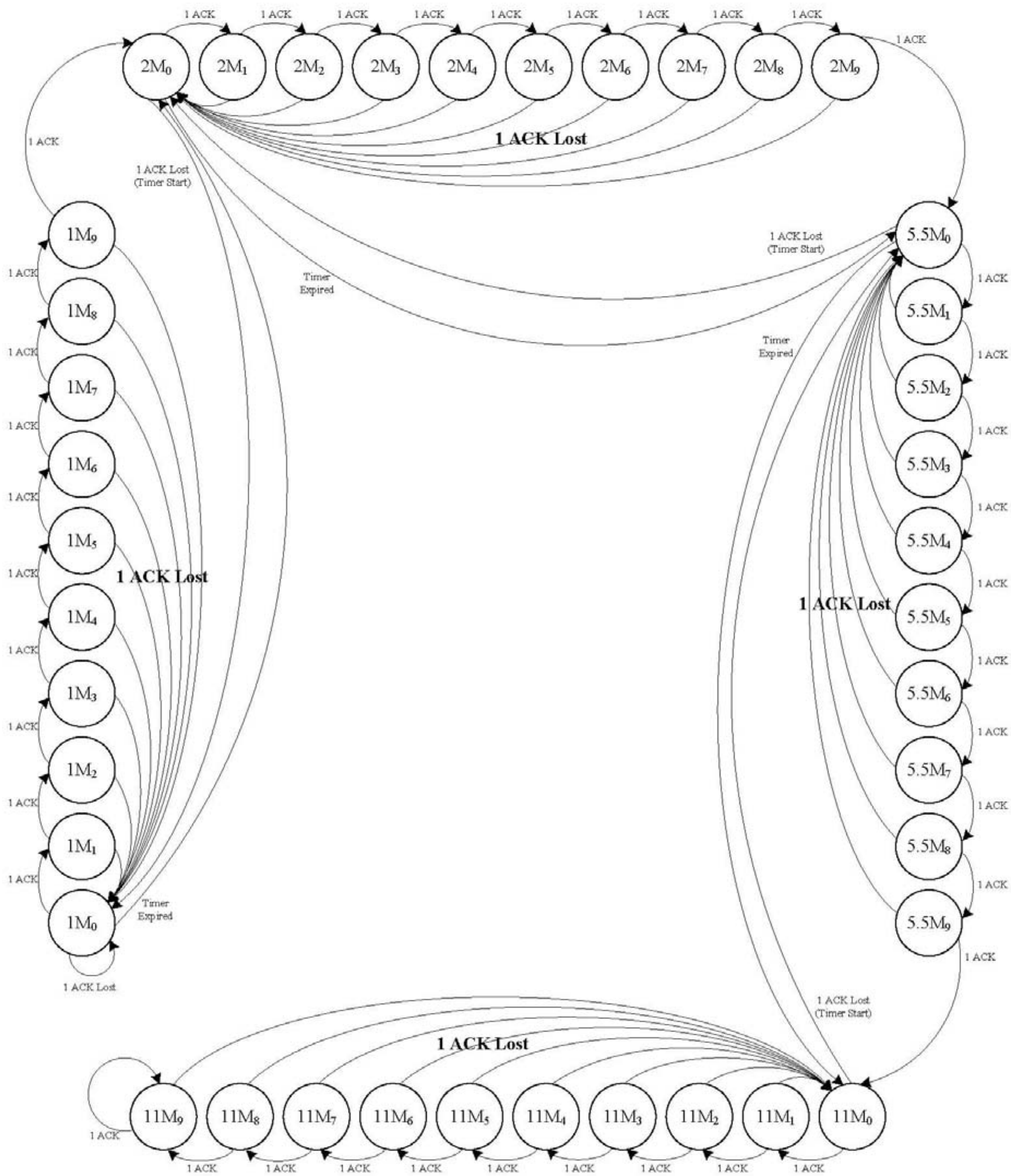


Figure 2.5 The Finite State Machine of ARF

3. Simulation Setup

3.1 Introduction to ns-2

Because of the complexity of time-varying channel conditions, node mobility, and various traffic patterns, building a complete analytical model to study network performance is difficult. On the other hand, a test bed with a large number of nodes is very expensive. Therefore, all the simulations in this thesis are based on ns-2 because of its specific features that will be mentioned later.

The Network Simulator (ns, also called ns-2) is a discrete event network simulator which was developed by UC Berkley, and it is widely used in academic research. ns-2 is an open-source software, and many modules have been developed for ns-2 by different researchers, and this has largely extended the capability of ns-2. Another advantage of ns-2 is that it is able to provide effective simulations that capture detailed information of network protocols.

The ns-2 with the new 802.11 module which supports IEEE 802.11 protocol [1] is used in all simulations. However, the original implementation of ns-2 is not sufficient to the investigation, and some modifications have been made to make it appropriate for this study. The modifications are summarized as follow:

1. It supports the multi-rate transmission and ARF rate-adaptation algorithm.
2. It contains a realistic radio propagation model that is suitable to simulate the mobile nodes deployed in urban environments.
3. It uses the FER (Frame Error Rate) -based reception model that reflects the error performance of 801.11a PHY modulation and coding schemes.

3.2 Simulation Setup

In this section, the models used in the simulation are described in detail from the following aspects: the multi-rate network model and parameters, mobility and propagation models, reception models, and simulated scenarios and traffic patterns.

3.2.1 PHY/MAC Parameters

The IEEE 802.11 family includes some different protocols, for example: 802.11a, 802.11b, 802.11g, and etc. All these standards employ the same MAC layer protocol, but they follow different standards at the PHY layer. The 802.11a standard is used for all simulations because 802.11a PHY layer supports eight transmission rates which are from 6 Mbps to 54 Mbps. Also, 802.11a is simpler than 802.11g standard because 802.11g needs to be compatible with 802.11b standard.

The Orthogonal Frequency-Division Multiplexing (OFDM) has been used as the modulation scheme in the IEEE 802.11a PHY. The 802.11a works in the 5 GHz frequency band and provides eight PHY modes with different modulation schemes – BPSK (Binary Phase-Shift Keying), QPSK (Quadrature Phase-Shift Keying), 16-QAM (Quadrature Amplitude Modulation), and 64-QAM. The maximum data rate is 54 Mbps, and others are 48, 36, 24, 18, 12, 9, and 6 Mbps. The data rates 6, 12, and 24 Mbps are mandatory (called Basic Data Rates). Table 3.1 lists eight modes of 802.11a PHY.

In Table 3.2, it lists some related 802.11a MAC/PHY parameters used in the simulation. When the size of the data frame is larger than the RTS threshold, the RTS/CTS exchange will be enabled before the data frame transmission. When the RTS threshold is set to 0, the RTS/CTS exchange will be enabled. On the contrary, when the

RTS threshold is set at 3000 octets, the RTS/CTS exchange will be disabled because the RTS threshold value is always larger than any legal MAC data frame (i.e. 2332 octets).

Table 3.1 Eight PHY Modes in IEEE 802.11a

Mode	Modulation	Code Rate	Data Rate (Mbits/s)	Bytes Per Symbol (BPS)
1	BPSK	1/2	6	3
2	BPSK	3/4	9	4.5
3	QPSK	1/2	12	6
4	QPSK	3/4	18	9
5	16-QAM	1/2	24	12
6	16-QAM	3/4	36	18
7	64-QAM	2/3	48	24
8	64-QAM	3/4	54	27

Table 3.2 Simulated Parameters in IEEE 802.11a

Parameter	Value
Preamble Length	16μs
PLCP Header Length	4μs
MAC Header Size	28 Bytes
Slot Time	9μs
Short Inter-Frame Space (SIFS)	16μs
DCF Inter-Frame Space (DIFS)	34μs
Clear Channel Assessment Time (CCA)	3μs
RxTx Turnaround Time	1μs
RTS Threshold	0 or 3000 Octets
Fragmentation Threshold	2100 Octets
Long Retry Limit	7
Short Retry Limit	7
Maximum Contention Window (CWmax)	1023μs
Minimum Contention Window (CWmin)	31μs
MSDU Lifetime	10s

3.2.2 Mobility and Propagation Model

The mobility models are very important for the performance study of wireless networks. These models describe the movement of stations, which includes stations' location, velocity, and destination change over time.

The Random Waypoint Mobility Model (RWPM) is used for most of our simulations. The RWPM is a popular and widely used mobility model in wireless network simulation [16], [2], [22]. It is a simple random model that describes the movement of stations in two-dimensional areas. All stations are deployed randomly, and pick up a random waypoint uniformly for each station. A constant velocity is also chosen randomly and uniformly between 0 and V, where V is the maximum velocity for each station. The waypoint and velocity of each station are chosen independently of others. After reaching the waypoint and waiting a certain pause time, the station chooses another new waypoint and velocity. It moves to this waypoint, and so on [16].

The radio propagation models describe the characterization of the radio wave propagation. According to the frequency, distance, and other conditions, the received signal power of each packet can be predicted. In ns-2, there are three radio propagation models which are Friis Free-Space Model, Two-Ray Ground Reflection Model and Shadowing Models. Actually, the Friis Free-Space Model and the Two-Ray Ground Model predict the mean received power at a distance. The Friis Free-Space Model is used to simulate the short distance propagation, and the Two-Ray Ground Reflection Model is for long distance propagation. In the real networking environment, the received power is a random variable because of the multi-path propagation effect, but these two propagation models are assumed to use ideal propagation conditions. So, the Shadowing

Model is an enhanced model that can present multi-path propagation effects in mobile networks, but it is still not sufficient to express the fluctuation of the channel condition by only using an added Gaussian random variable [6]. On the other hand, an extensive measurement campaign has shown that using a Rayleigh or Ricean distribution can model the signal deviation better. Ricean distribution is used if there is a dominant stationary signal component present, such as a line-of-sight propagation path; otherwise, Rayleigh distribution is more suitable [25].

This implementation of the radio propagation model includes two parts: log-distance path loss model [25] and the Ricean Propagation Model [23].

The received signal power can be calculated as a function of distance by using the path loss model, and it is possible to predict the SNR for most mobile communication systems. By these propagation models, the average received signal power will decrease logarithmically with distance. The log-distance path loss can be defined as (1).

$$P_{r_d}[dBm] = P_{r_{d_0}}[dBm] + 10 \cdot n \cdot \log\left(\frac{d}{d_0}\right), \tag{1}$$

where *n* is the path loss exponent that indicates the rate at which the path loss in distance d and the *n* value depends on the different propagation environments, d_0 is the reference distance which is the determined distance close to the transmitter, and d is the distance between the transmitter and the receiver. The $P_{r_{d_0}}$ (in *watt*) is calculated by the Friis Free-Space Model, and for a unique distance *d*, the received signal power for above propagation models can be calculated by (2).

$$P_{r_{d_0}}[watt] = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \tag{2}$$

In (2), P_t is the signal power of transmitting and set as 15 *dBm* in our simulations, G_t and G_r are the antenna gain of the transmitter and receiver, L is the system loss factor

(G_t, G_r, and $L = 1$ in our simulations). To simulate a mobile network in an urban area, the path loss exponent n is set as 3 and d_0 is set as 1 meter in simulations. Table 3.3 lists path loss exponents for some propagation environments.

Table 3.3 Path Loss Exponent for Propagation Environments

Environment	Path loss exponent *n*
Free Space	2
Urban area cellular radio	2.7 ~ 3.5
Shadowed urban cellular radio	3 ~ 5
In building line-of-sight	1.6 ~ 1.8
Obstructed in building	4 ~ 6
Obstructed in factories	2 ~ 3

After the P_{r_d} is calculated in (1), the Ricean fading value is applied to the received signal power by looking up a simple pre-computed table [23]. The result after the Ricean fading effect is

$$P_{r_d}^{*}[dBm] = P_{r_d}[dBm] + 10 \cdot \lg(F_{Ricean}), \quad (3)$$

where F_{Ricean} is the fading envelope factor resulted by the Ricean Propagation Model.

3.2.3 Reception Model

In ns-2, at the PHY layer of each station there are two thresholds, the receiving power threshold and the carrier sense power threshold. The received packets will be dropped or received by comparing with these thresholds. This is a simple threshold-based model, which compares the power with receiving threshold (*RxThreshold*) and carrier-sense threshold (*CSThreshold*). By these thresholds, the receiver can determine whether one packet is received correctly or not. If the signal power of a packet is less than *CSThreshold*, this packet will be discarded at PHY layer immediately. If the signal power is less than *RxThreshold* and larger than *CSThreshold*, this packet will also be received but discarded as corrupted at the PHY layer later. Otherwise, this packet will be received correctly and delivered to the MAC layer directly. This threshold-based reception model is too simple and does not consider the issue which is about the error performance of 802.11 devices. In the real network environment, the error performance is more complicated than the threshold-based model. Some device-dependent factors, external interference, and especial the PHY modulation modes and coding schemes need to be considered.

To simulate a more realistic network environment, the FER-based reception model (Frame Error Rate) is employed in the simulations. If the receiving power of a frame is larger than the *RxThreshold* and not discard by the capture effect, the FER of this received frame will be calculated and decide to deliver it to the MAC layer by comparing it with a general random number. Figure 3.1 presents the procedure of the frame reception model, and Figure A.1 and Figure A.2 present the detailed procedure of the frame reception model.

First of all, the SINR of the incoming frame is calculated as

$$SINR = \frac{P_{r_i}}{Noise\ Floor + \sum_{j=1, j \neq i}^{n} P_{r_j}}, \quad (4)$$

where P_{r_i} is the received power of the incoming frame, which is from (3), and $\sum_{j=1, j \neq i}^{n} P_{r_j}$ is the sum of the received power of all other ongoing frames. The received power of other frames is considered as the noise interference to the incoming frame.

Second, the BER (Bit Error Rate) is calculated based on the SINR from (4) and the transmission mode which the received frame used in Table 3.1.

In the BER calculation, two different formulas are used for different transmission modes. One is for the PSK modulation scheme (i.e. BPSK and QPSK), and the other one is for the QAM modulation scheme (i.e. 16-QAM and 64-QAM).

For BPSK and QPSK, the formula of BER is as

$$P_b^{PSK} = Q\left(\sqrt{\frac{2E_b}{N_0}}\right), \tag{5}$$

where E_b is the energy per bit and $N_0/2$ is the noise power spectral density (*W/Hz*). The *Q*-function is defined as following:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-t^2/2}dt\,, x \geq 0, \tag{6}$$

and E_b/N_0 can be calculated by the following formula:

$$E_b/N_0 = SINR \times \frac{Signal\ Spread(Hz)}{Data\ Rate(bps)}, \tag{7}$$

where SINR is from (4) and use Signal Spread as 20 *MHz* for 802.11a in our simulations.

For 16-QAM and 64-QAM with a Gray-coded assignment of bits to symbols, the BER for *M*-QAM modulation scheme is approximate as

$$P_b^{QAM}(M) = 1 - \left[1 - \frac{4}{logM}\left(1 - \frac{1}{\sqrt{M}}\right) \cdot Q\left(\sqrt{\frac{3 \cdot logM}{M-1} \cdot \frac{E_b}{N_0}}\right)\right], \tag{8}$$

where M is set as 16 for 16-QAM and 64 for 64-QAM respectively. E_b/N_0 is calculated from (7).

Third, the PER is calculated using the formula which is an upper bound of error probability of the packet [24]. This error probability is under the assumption of binary convolutional coding and hard-decision Viterbi decoding with independent errors at the channel input. For an *l*-octet long chunk of frame to be transmitted using PHY mode *m*, the boundary of the error probability is

$$P_e^m(l) \leq 1 - [1 - P_u^m]^{8l}, \tag{9}$$

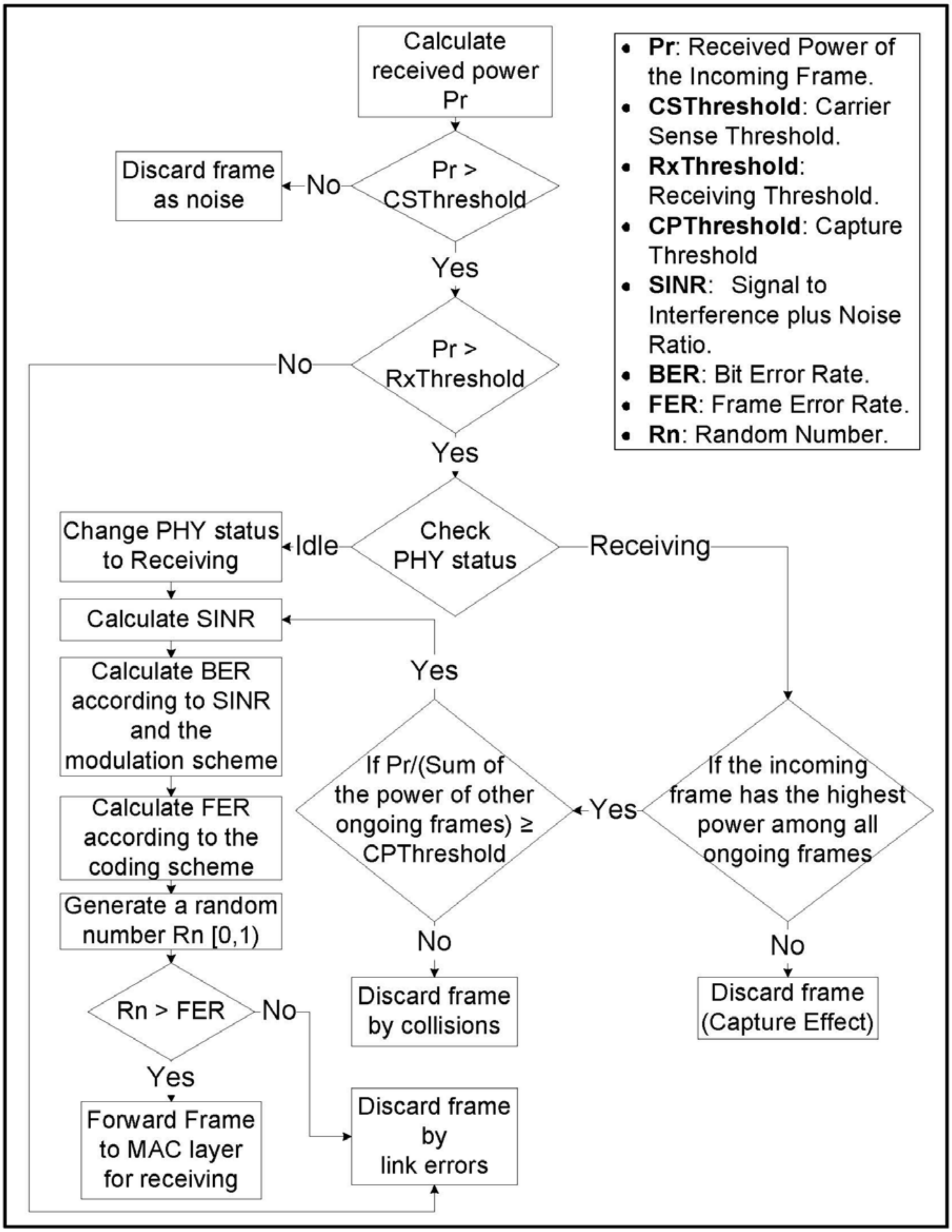


Figure 3.1 The Procedure of the FER-Based Frame Reception Model

where the union bound P_u^m of the first-event error probability is given by

$$P_u^m(l) = \sum_{d=d_{free}}^{\infty} a_d \cdot P_d(l), \tag{10}$$

where d_{free} is the free distance of convolutional code, a_d is the total number of error events of weight *d*, and $P_d(l)$ is the probability that an incorrect path at distance *d* from the correct path, which is chosen by Viterbi decoder, as defined as

$$P_d(l) = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \cdot \rho^k \cdot (1-\rho)^{d-k}, if\ d\ is\ odd \\ \frac{1}{2} \cdot \binom{d}{d/2} \cdot \rho^{d/2} \cdot (1-\rho)^{d/2} \\ + \sum_{k=d/2+1}^{d} \binom{d}{k} \cdot \rho^k \cdot (1-\rho)^{d-k}, if\ d\ is\ even \end{cases}, \tag{11}$$

where ρ is the BER for the modulation scheme which is used at PHY layer, and it can be calculated by (5) or (8). Table 3.4 is the parameters for calculating $P_e^m(l)$ in different modulation schemes.

Table 3.4 Parameters of PSK and QAM Modulation Schemes

Mode	M	dFree	adFree	Signal Spread	Rate	Coding Rate
1	-	10	11	20×10^6	6×10^6	$1/2$
2	-	5	8	20×10^6	9×10^6	$3/4$
3	4	10	11	20×10^6	12×10^6	$1/2$
4	4	5	8	20×10^6	18×10^6	$3/4$
5	16	10	11	20×10^6	24×10^6	$1/2$
6	16	5	8	20×10^6	36×10^6	$3/4$
7	64	6	1	20×10^6	48×10^6	$2/3$
8	64	5	8	20×10^6	54×10^6	$3/4$

The 802.11a frame is separated into two parts and calculates their BER individually. One is the PLCP (Physical Layer Convergence Procedure) header of the frame which is

always transmitted in mode 1, and the rest part of the frame is transmitted in other modes. Then, the BER of each frame can be combined from each part of the error rate.

Finally, the $P_e^m(l)$ function is used to evaluate FER with the equation which is given by

$$\mathrm{FER} = 1 - \prod\left(1 - P_e^m(l)\right). \tag{12}$$

3.2.4 Simulation Scenarios and Traffic Model

In the simulations, I focus on infrastructure mode and IEEE 802.11a standard, and I also want to investigate how the RTS/CTS exchange could impact the performance of the rate-adaptation mechanism. In this situation, all stations are deployed in a small area (smaller than the carrier sense range of about 135 meters), and then the hidden node problem will not influence the simulations. Therefore, the hidden node problem could be ignored. One node as an AP is placed in the center of the area and up to 60 nodes as stations randomly in a square area which is 60×60 meter^2, 80×80 meter^2, or 100×100 meter^2. RWPM is used as the mobility of each station, and the velocity of each station is random from 0 to 10 meter/second.

All traffic flows are from each station as the sender to the AP as the receiver which is located in the center of each scenario. UDP and TCP are as the applications in the simulations. For UDP, the aggregated traffic load in the network can be simply expressed as

$$E(n, l, \tau) = n \times l \times \left(\frac{1}{\tau}\right), \tag{13}$$

where n is the number of nodes which are sending data, l is the average data packet size, and τ is the time interval between packets. The traffic load will be vary with the changing value of n, l, or τ. For TCP, only the number of nodes and average data packet size are changed because TCP is a self-adaptive application. TCP New Reno is used in some of the simulations, which is based on TCP Reno and modifies the action taken when receiving new ACKs.

4. The Impact of RTS/CTS Exchange

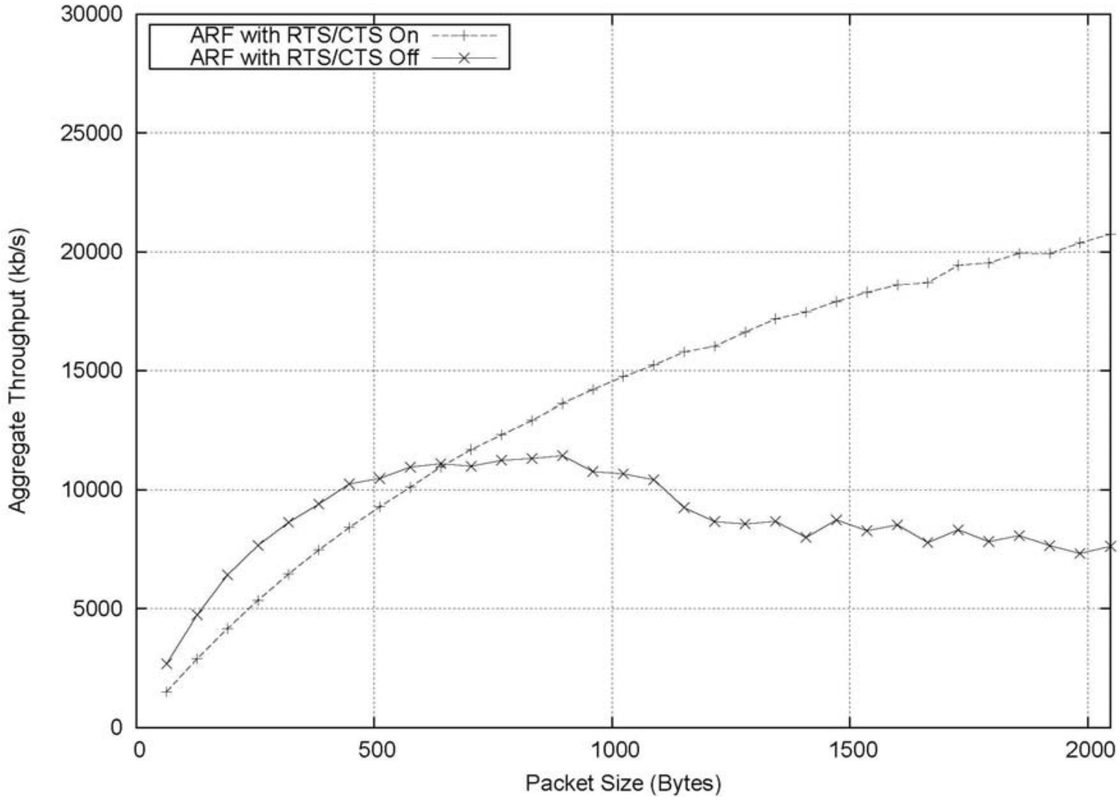
Several scenarios are set up to simulate the different conditions in 802.11 multi-rate networks. Through all these simulations, the objective was to observe how the RTS/CTS exchange could affect the performance of the 802.11 WLANs with multi-rate adaptation. In each scenario, the performance in two cases was compared. The first case was one in which the RTS/CTS exchange is turned on while the other case has RTS/CTS turned off. By this comparison, I can investigate whether the RTS/CTS exchange is necessary in multi-rate 802.11 networks or not when there is no any hidden node problem. If the RTS/CTS exchange is necessary, I also want to figure out how much it influences network performance under different situations. In the comparison of network performance, the network-wise aggregated throughput is used as the major performance metric, not an individual flow throughput. The reasons are: (1) Each traffic flow will have its own optimal transmitting strategy that will degrade the whole network performance, which is called the performance anomaly of multi-rate networks [7]. (2) The network-wise aggregated throughput is more suitable to present the whole network performance than the throughput of some individual flows. Even so, some examinations use the throughput of the individual flow, for example, the fairness issue.

ARF protocol is employed to be the rate adaptation scheme in all simulations because ARF is a widely used rate adaptation scheme in most 802.11 devices. I believe that this can provide the insights which could apply to other statistics-based rate adaptation schemes.

4.1 The Rate Avalanche Effect and the Impact of Packet Size

At first, an example demonstrates a phenomenon which is called rate avalanche. In an 80×80 meter^2 area, an AP is installed in the center (i.e. (40, 40)) and 40 802.11a nodes are randomly deployed in this area. Each node has a UDP-based traffic flow to the AP. Each traffic flow starts the transmission at 0s and stops at 30s, and the packet arrival rate is 200 packets/second (or the packet interval is 5 *ms*). All nodes are static during the transmission time, and all nodes have the RTS/CTS exchange turned on. To do the exact same experiment with different packet sizes, from 64 Bytes to 2048 Bytes with intervals of 64 Bytes. To repeat the all experiments with the same settings and turn off the RTS/CTS exchange.

Figure 4.1 is showing the comparison of the aggregated throughput between the case with RTS/CTS-on (denoted as the RTS/CTS exchange turned on) and the case with RTS/CTS-off (denoted as the RTS/CTS exchange turned off). From the figure, it shows the aggregated throughput of RTS/CTS-on is lower than RTS/CTS-off from the packet sizes 64 Bytes to 640 Bytes. Otherwise, the throughput of RTS/CTS-off is much lower than RTS/CTS-on after the packet size is larger than 640 Bytes. This result from above is not what was expected when there is not any hidden node problem. It was expected that RTS/CTS-off would have a better performance than RTS/CTS-on because of the transmission overhead of the RTS/CTS exchange. Figures 4.2 and 4.3 give some idea about this result. These figures compare the number of collisions and the cumulative distribution of data rates used for RTS/CTS-on and RTS/CTS-off, where the packet size is 1024 Bytes. (1) Figure 4.2 shows that RTS/CTS-on reduces the number of collisions because the RTS frames are much shorter than most of the data frames. Thus, the



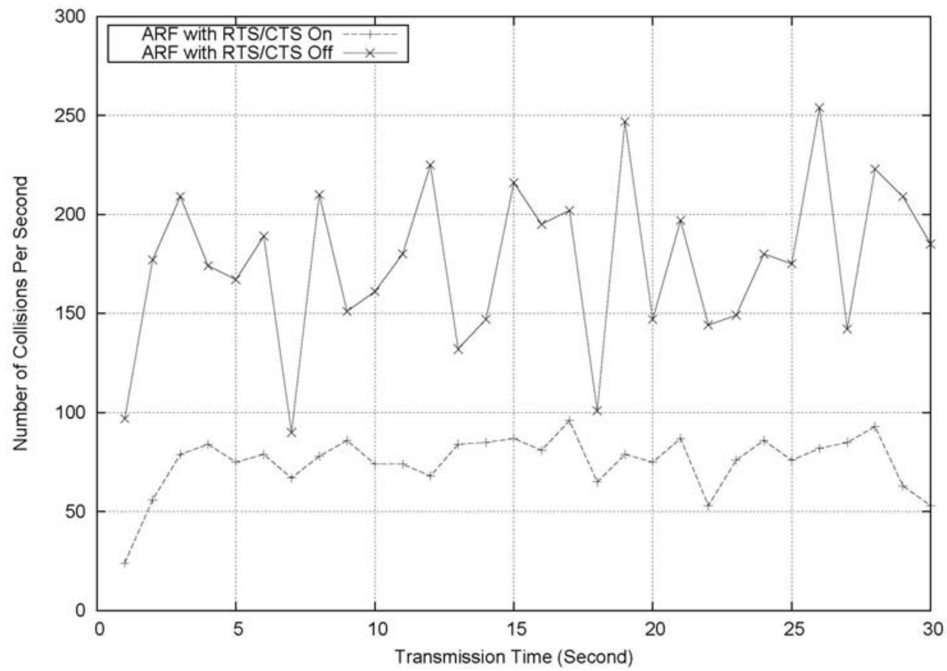
Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l varies

Figure 4.1 Aggregated Throughput: RTS/CTS-On vs. RTS/CTS-Off

probability of collision of the RTS frames is lower than the probability of collision of the data frame. After a RTS frame is successfully received by the receiver, the channel will be reserved for the following CTS and data frames. Then, the probability of a successful transmission will be increased, and it also reduces the retransmission for saving the channel resources. (2) In Figure 4.3, the RTS/CTS-off has the higher percentage of using the lower rates to transmit the data frames than the RTS/CTS-on. In ARF, the transmission rate will increase by the statistics of acknowledged/unacknowledged data transmissions. When the RTS/CTS is off, the collision will cause the unacknowledged transmission and the rate will be dropped. When the RTS/CTS is on, most of the collisions are caused by the RTS frames, but the collisions of the RTS frame will not cause the unacknowledged data transmissions. The data rate will not be dropped. That is why RTS/CTS-on will have higher percentage of using higher data rates. Figure 4.4 and Figure 4.5 are the data rates used over time for every data packets in RTS/CTS-on and RTS/CTS-off respectively. Figure 4.6 is the cumulative distribution of the SINR which is measured at the AP for all frames received with or without error. From this figure, the SINR cannot be the reason of the difference in rates because the SINR for both cases is very similar.

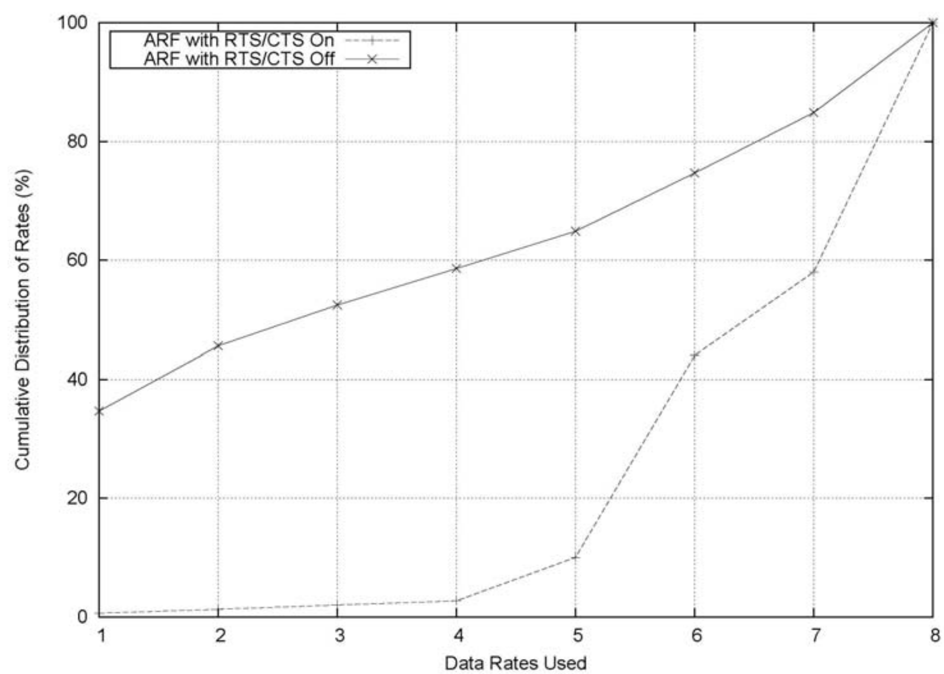
The RTS/CTS transmission overhead will always happen in all packet sizes when the RTS/CTS is on. When the RTS/CTS is off, the rate avalanche will also happen in all packet sizes. The influence will depend on the size of different data packets. The effect of the RTS/CTS transmission overhead will be less severe when the packet size increases, but the effect of rate avalanche will be more severe when the packet size increases. That is the reason the two curves cross at a point in Figure 4.1, and the packet size of this cross-point could be used as the optimal RTS threshold.



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l=1024 Bytes

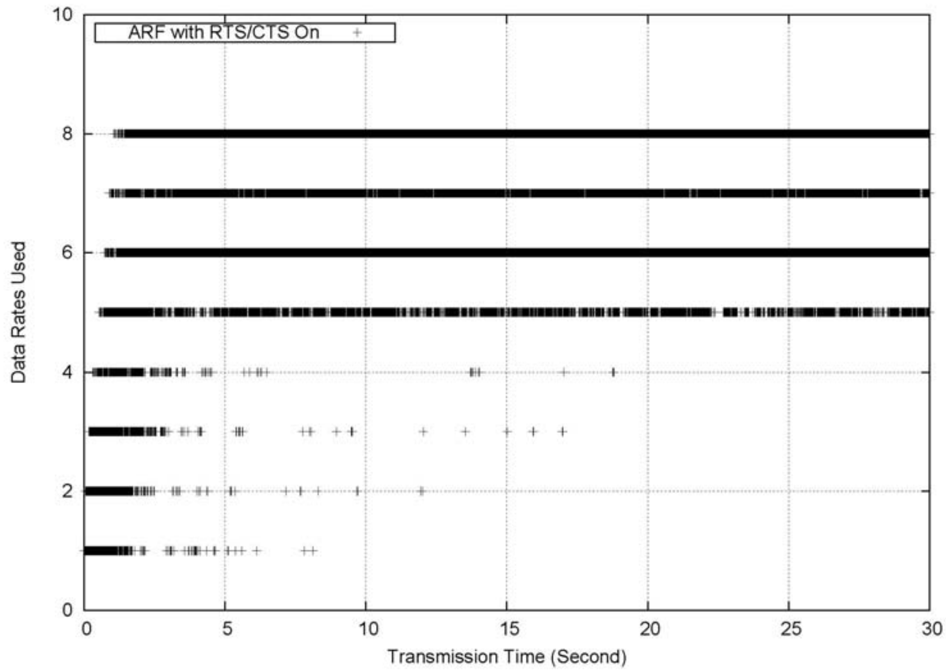
Figure 4.2 Number of Collisions Per Second



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l=1024 Bytes

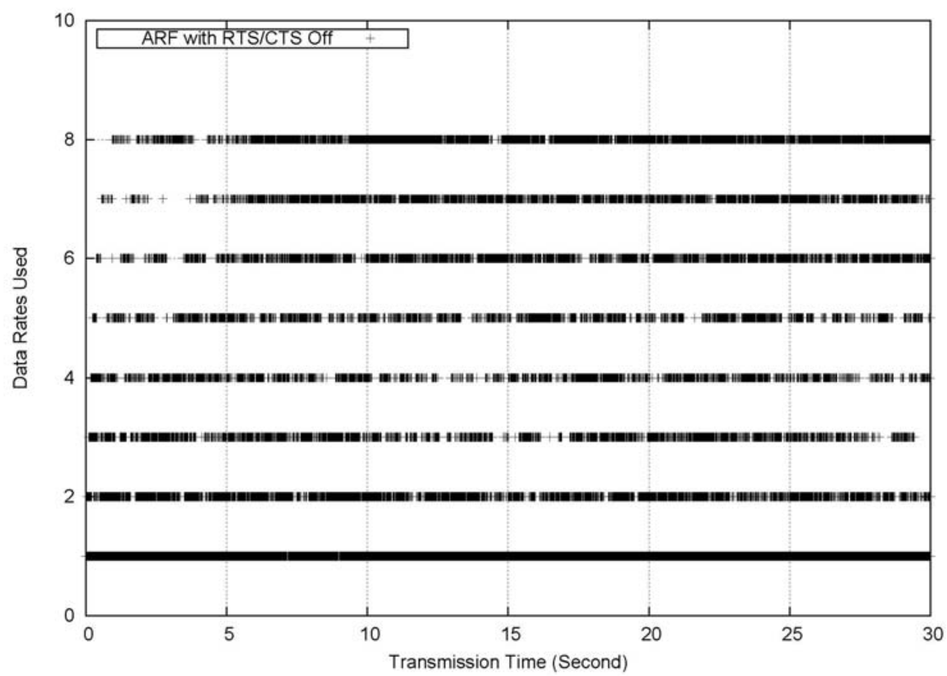
Figure 4.3 Cumulative Distributions of Data Rates Used



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l=1024 Bytes

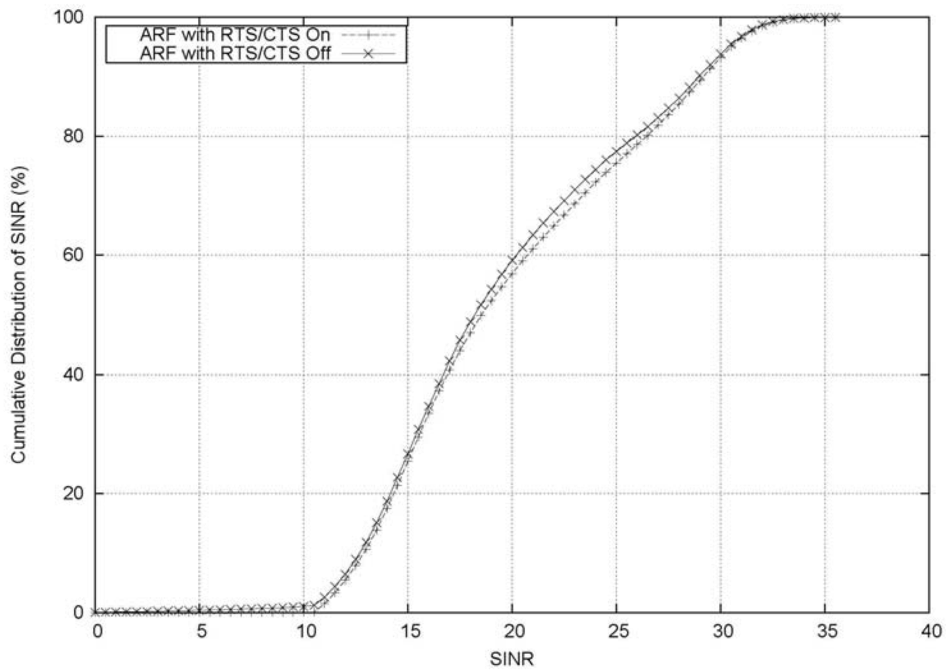
Figure 4.4 Data Rates Used for RTS/CTS-On



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l=1024 Bytes

Figure 4.5 Data Rates Used for RTS/CTS-Off



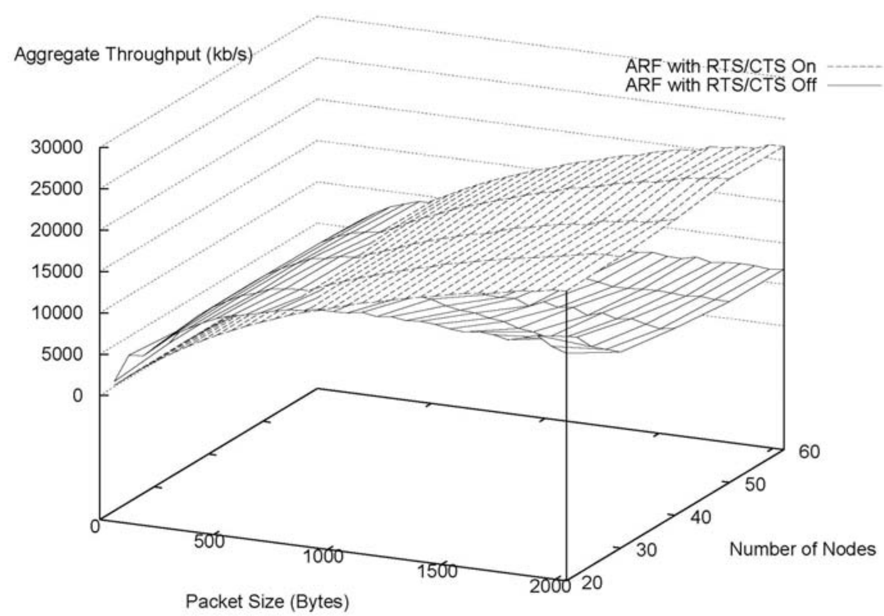
Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l=1024 Bytes

Figure 4.6 Cumulative Distributions of the SINR

4.2 The Impact of Node Numbers

This part is to investigate how much node numbers can affect the network performance in RTS/CTS-on and RTS/CTS-off. The number of nodes varies from 20 to 60 in this group of experiments, and other conditions will be same as in Chapter 4.1. All 802.11a nodes are deployed randomly in an 80×80 meter^2 area, and an AP is placed in the center. All nodes are with UDP-based application, and the packet interval is 5 *ms*. The result is shown as Figure 4.7, and the packet sizes which correspond to the cross-points highly depend on node numbers of nodes. When the node numbers are larger, the cross-points shift toward to the smaller packet sizes. That means the RTS/CTS-on will have better performance than RTS/CTS-off in an area with a high density of nodes because a higher density of nodes will have more contentions which causes more collisions. Then, more retransmissions will happen and rate avalanche will be more serious.



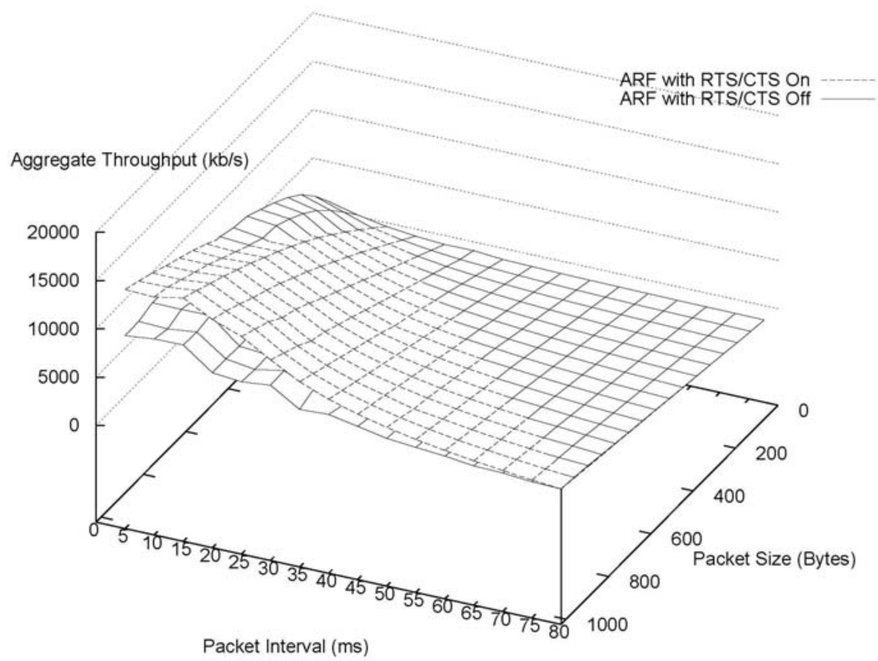
Deployment area: 80×80 m^2

Traffic load: τ=5 ms, n and l are vary

Figure 4.7 The Impact of Node Numbers

4.3 The Impact of Packet Arrival Rate

In this part, the goal is to investigate how much the packet arrival rate could affect the network performance in RTS/CTS-on and RTS/CTS-off. In this group of experiments, the focus is on the area around cross-points, and the packet sizes are various from 64 Bytes to 1024 Bytes with intervals of 64 Bytes. The result is shown in Figure 4.8, and the result is very similar when $\tau = 5$ *ms* and $\tau = 10$ *ms*. Starting from $\tau = 15$ *ms*, the cross-points are shifting toward larger packet sizes when τ is getting larger. In this figure, the aggregated throughput of RTS/CTS-off over RTS/CTS-on is very slight because the traffic of the network starts to be under-loaded when τ is larger than 15 *ms*. This situation is more obviously happened in the case with the smaller packet sizes.



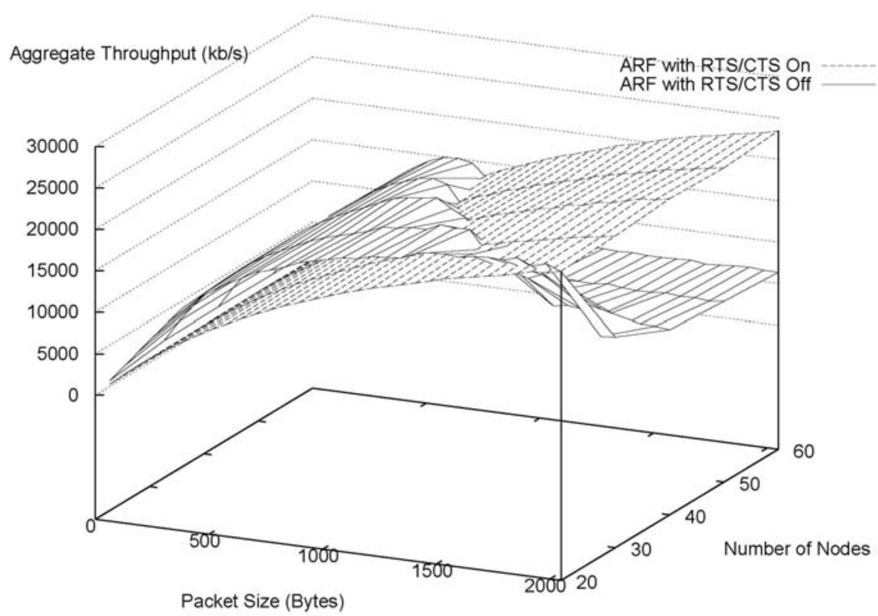
Deployment area: 80×80 m^2

Traffic load: n=40, τ and l vary

Figure 4.8 The Impact of Packet Arrival Rate

4.4 The Impact of Node Geographical Distributions

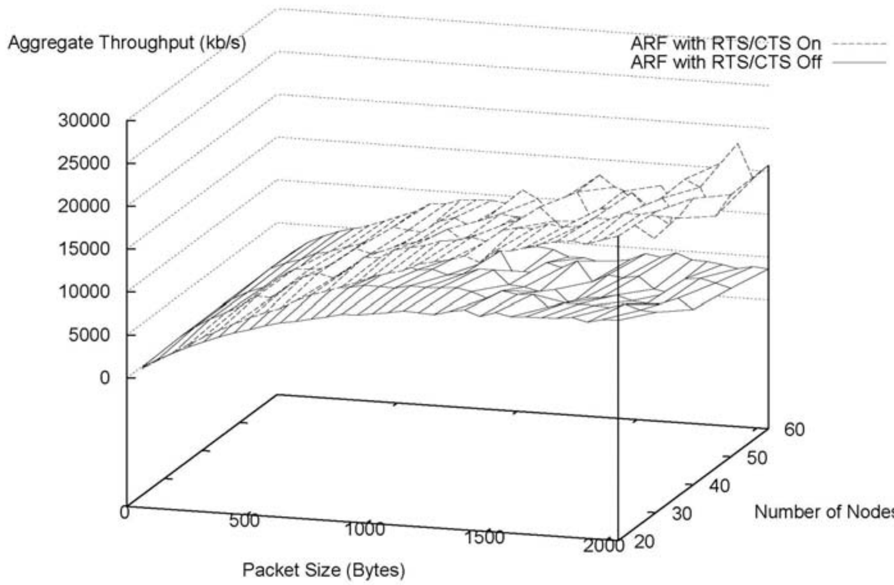
In previous experiments, all 802.11a nodes were randomly deployed in an 80×80 meter ^{2} area. In this part, the goal is to study how much the geographical distribution could affect the network performance in RTS/CTS-on and RTS/CTS-off. Nodes are deployed in different size areas, and Figure 4.9 and Figure 4.10 present the results for 60×60 meter^2 and 100×100 meter^2 respectively. From these figures, which are 80×80 meter^2, 60×60 meter^2 and 100×100 meter^2, when the deployment area is getting larger, the cross-points shift toward the smaller packet sizes. That is because when the nodes are deployed in wider areas, these nodes have more chances to use the lower rates to transmit the data frames. For this reason, the effect of the transmission overhead of the RTS/CTS exchange is getting smaller because of the difference between the transmission rates for data frames and the RTS/CTS exchanges are getting smaller.



Deployment area: 60×60 m^2

Traffic load: τ=5 ms, n and l vary

Figure 4.9 The Impact of Node Geographical Distribution (60×60 m^2)



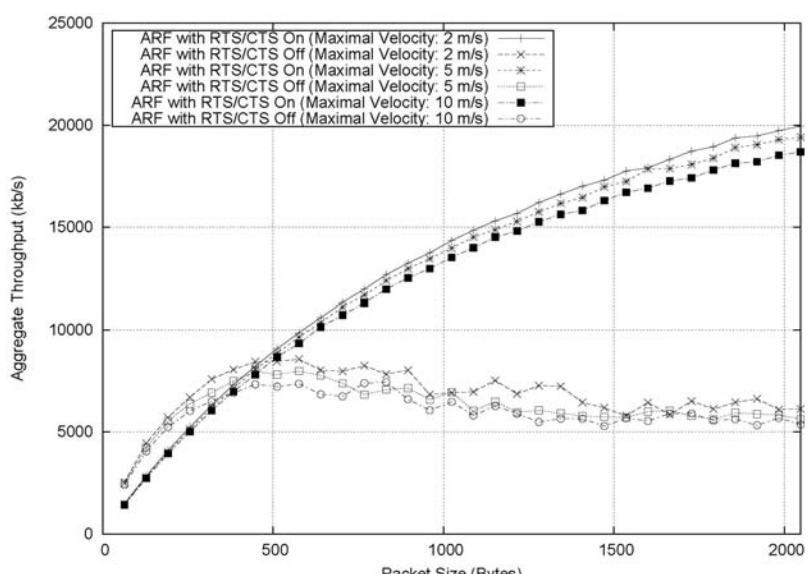
Deployment area: 100×100 m^2

Traffic load: τ=5 ms, n and l vary

Figure 4.10 The Impact of Node Geographical Distribution (100×100 m^2)

4.5 The Impact of Node Mobility

In all simulations presented previously, all nodes are static during the transmission time. In this part, the goal is to investigate how much the node mobility could affect the network performance in RTS/CTS-on and RTS/CTS-off. Three mobility models are created with a different maximum velocity of 2, 5, and 10 meters/second, and this maximum velocity is a parameter defined in RWPM mobility model to limit the random moving speed of each node. These three mobility models are employed in the experiments, 40 nodes are randomly deployed in an 80×80 meter^2 area and then follow the mobility models to move in this area. The result is shown in Figure 4.11, and the higher moving speed degrades the network performance slightly, either in RTS/CTS-on or RTS/CTS-off. This figure also shows that when the random moving speed is faster, the cross-points shift toward the smaller packet sizes. That is because the faster moving nodes will cause the received signal to fluctuations more at the receiver due to the



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l varies

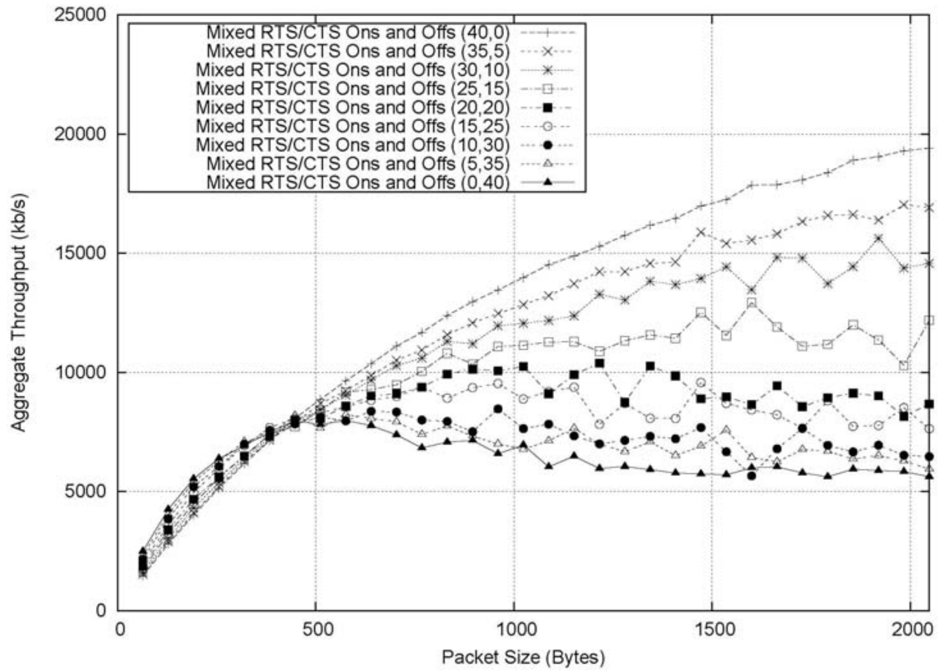
Figure 4.11 The Impact of Node Mobility

Doppler shifting and multi-path propagations.

4.6 Mixed RTS/CTS Ons and Offs

In previous simulations, all nodes have the same action of the RTS/CTS exchange, either all nodes have turned on the RTS/CTS or all nodes have turned off the RTS/CTS. In this part, the goal is to study the effect when all nodes are not with the same action of the RTS/CTS exchange. At this time, part of the nodes will be RTS/CTS-on and others will be RTS/CTS-off. I set up 7 combinations of all 40 nodes, which are (5, 35), (10, 30), (15, 25), (20, 20), (25, 15), (30, 10), and (35, 5). For example, (5, 35) means 5 nodes are RTS/CTS-on and 35 nodes are RTS/CTS-off. Figure 4.12 shows the comparison of 7 combinations with the previous experiments in which are nodes are RTS/CTS-on or RTS/CTS-off. The result shows the more nodes with RTS/CTS-on, the better the network performance. The cross-points are not significantly different among these combinations.

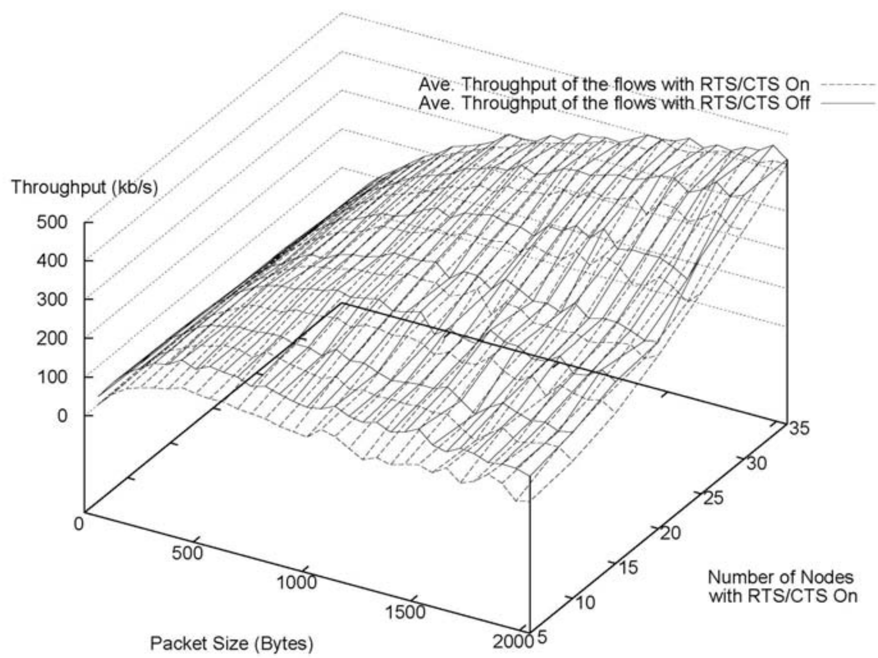
In Figure 4.13, it shows the average throughputs of RTS/CTS-on flow and RTS/CTS-off flow respectively. From this figure, the average throughput of RTS/CTS-off has a better performance than RTS/CTS-on in all combinations. A node is simply inferred as a selfish node. If it turns on the RTS/CTS all the time and tries to get better performance than other competing nodes, it could actually lower its own performance and also degrade the network performance.



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l varies

Figure 4.12 Mixed RTS/CTS Ons and Offs (Aggregated Throughput)



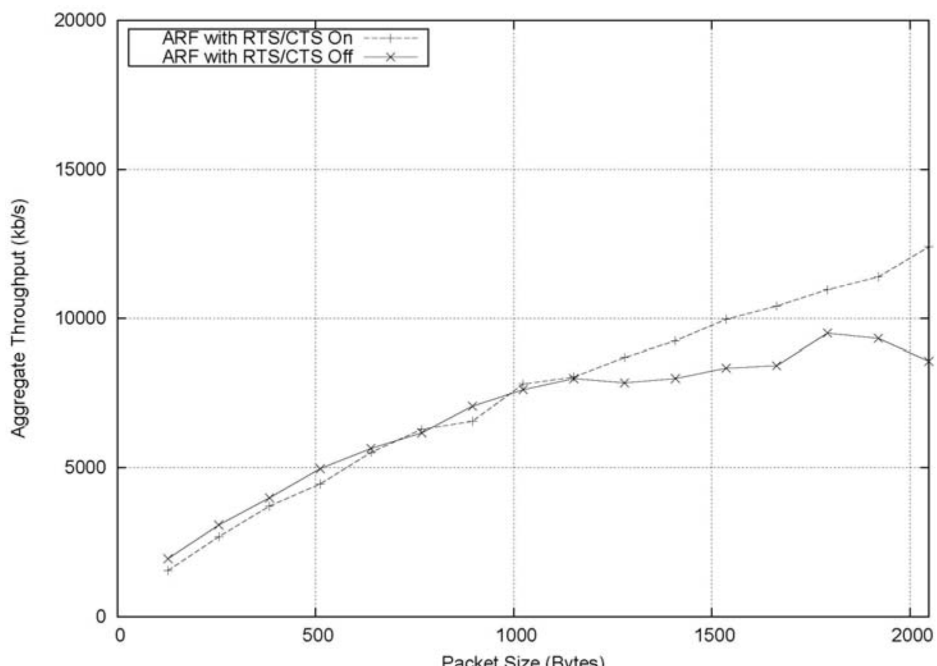
Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l varies

Figure 4.13 Mixed RTS/CTS Ons and Offs (Average Throughput)

4.7 TCP-based Applications

All previous simulations are based on UDP applications. In this part, TCP-based applications are employed, TCP New Reno and selected ACKs are used, instead of UDP-based applications in Figure 4.1, and other conditions are exactly same. The result is shown in Figure 4.14, and the network performance of RTS/CTS-on is also better than RTS/CTS-off when the packet sizes are larger than the cross-point, but the difference is not as big as UDP-based applications. The effect of rate avalanche on TCP-based applications is less severe than on UDP-based applications because the TCP-based applications are capable of self-adaptability to reduce the contentions in a shared network channel.



Deployment area: 80×80 m^2

Traffic load: n=40, τ=5 ms, and l varies

Figure 4.14 TCP-Based Applications

4.8 Summary

I summarized all the results that were found from the simulations, which are about the impact of the RTS/CTS exchange on the performance of multi-rate 802.11 WLANs.

- Turning off the RTS/CTS mechanism in heavily-loaded multi-rate 802.11 WLANs could degrade network performance, particularly if the rata avalanche effect is the major cause of the performance degradation.
- The impact of the RTS/CTS exchange in lightly-loaded multi-rate 802.11 WLANs is negligible.
- TCP-based applications have less severe effect of rate avalanche than UDP-based applications because TCP-based applications have the ability of self-adaptation.
- With all factors considered, turning on the RTS/CTS mechanism will lead to a higher chance of getting the better performance than disabling the RTS/CTS mechanism.
- If using a pre-configured RTS threshold to employ the dynamic RTS/CTS exchange, it will only lead to sub-optimal network performance. This is because the optimal RTS threshold depends on several factors such as the number of competing nodes, the geographic distribution of nodes, and node mobility. However, all these factors are vary in a real network.

5. Conclusion

The RTS/CTS exchange has been disabled in most 802.11 WLANs devices because of transmission overhead. It might be a good strategy for single-rate networks, but it could significantly degrade the performance of multi-rate networks. This study reveals that a phenomenon called rate avalanche could happen when the RTS/CTS mechanism is turned off in a heavily-loaded multi-rate WLANs. In this situation, even if there is not any hidden node problem, high collision rates lead to packet retransmissions and lower transmission rates being used; retransmissions and longer channel occupation time will increase the channel contention, which will yields more collisions. This vicious cycle could significantly degrade the network performance. Driven by this discovery, I conducted an investigation on the impact of the RTS/CTS exchange on the performance of multi-rate 802.11 WLANs. This investigation was based on realistic propagation and reception models and ARF rate-adaptation. I simulated various scenarios/conditions for studying their impact on the performance for RTS/CTS-on and RTS/CTS-off respectively.

This investigation leads to some conclusions about the impact of the RTS/CTS exchange on multi-rate 802.11 wireless networks. (1) Turning on the RTS/CTS mechanism in heavily-loaded multi-rate 802.11 WLANs could diminish the effect of rate avalanche. (2) The impact of the RTS/CTS exchange in lightly-loaded multi-rate 802.11 WLANs could be negligible. (3) Because TCP-based applications have the ability of self-adaptation, the impact of the RTS/CTS exchange on TCP-based applications is less severe than on UDP-based applications. (4) Keeping the RTS/CTS exchange on lead to a higher chance of obtaining better performance than keeping the RTS/CTS exchange off. (5) A pre-configured RTS threshold could be used to employ the dynamic RTS/CTS exchange and will lead to sub-optimal performance. Hopefully, these insights might help wireless network protocol designers enhance the performance of 802.11 WLANs.

6. References

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Appendix

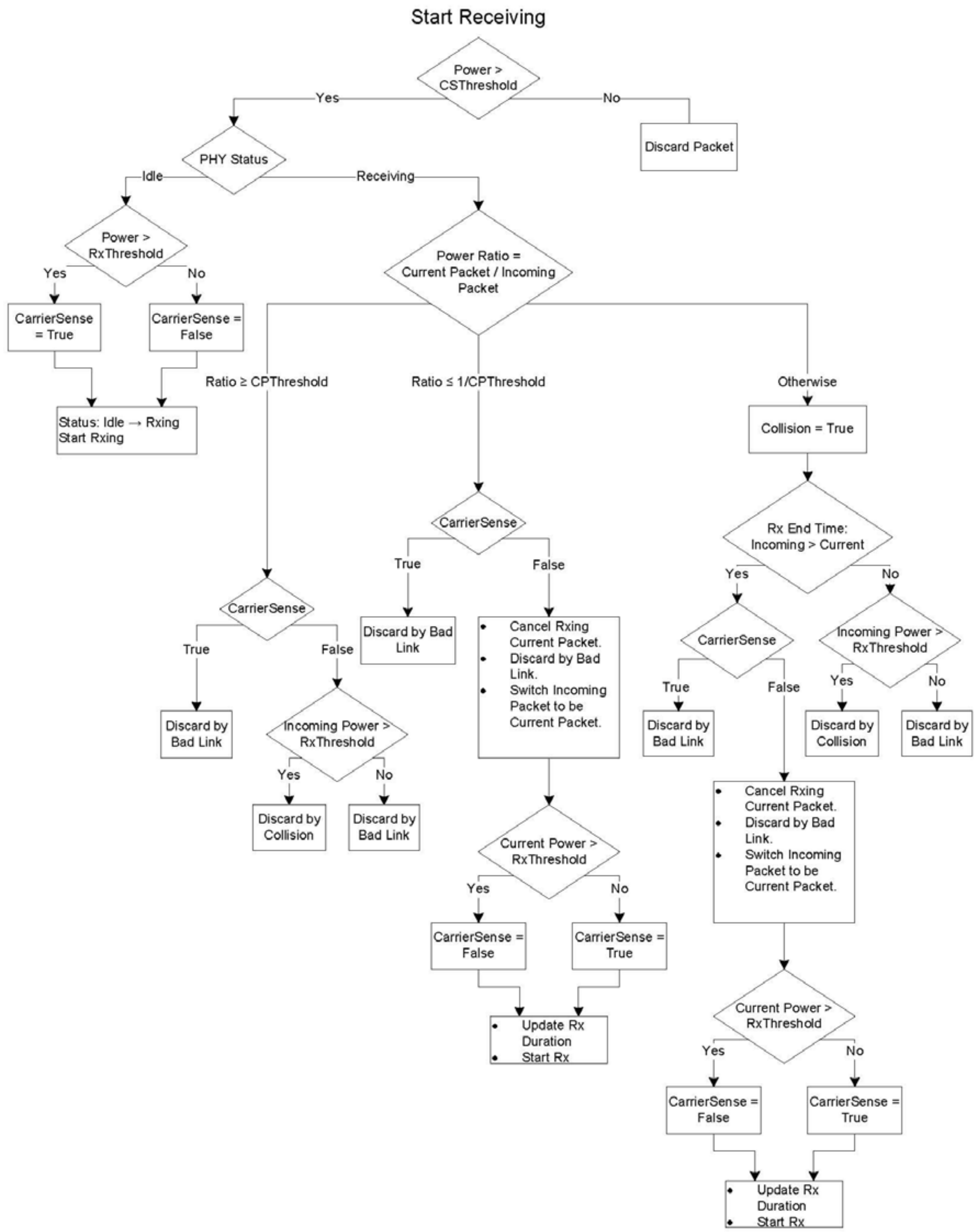

Figure A.1 The Procedure of the Starting Receiving in FER-Based Reception Model

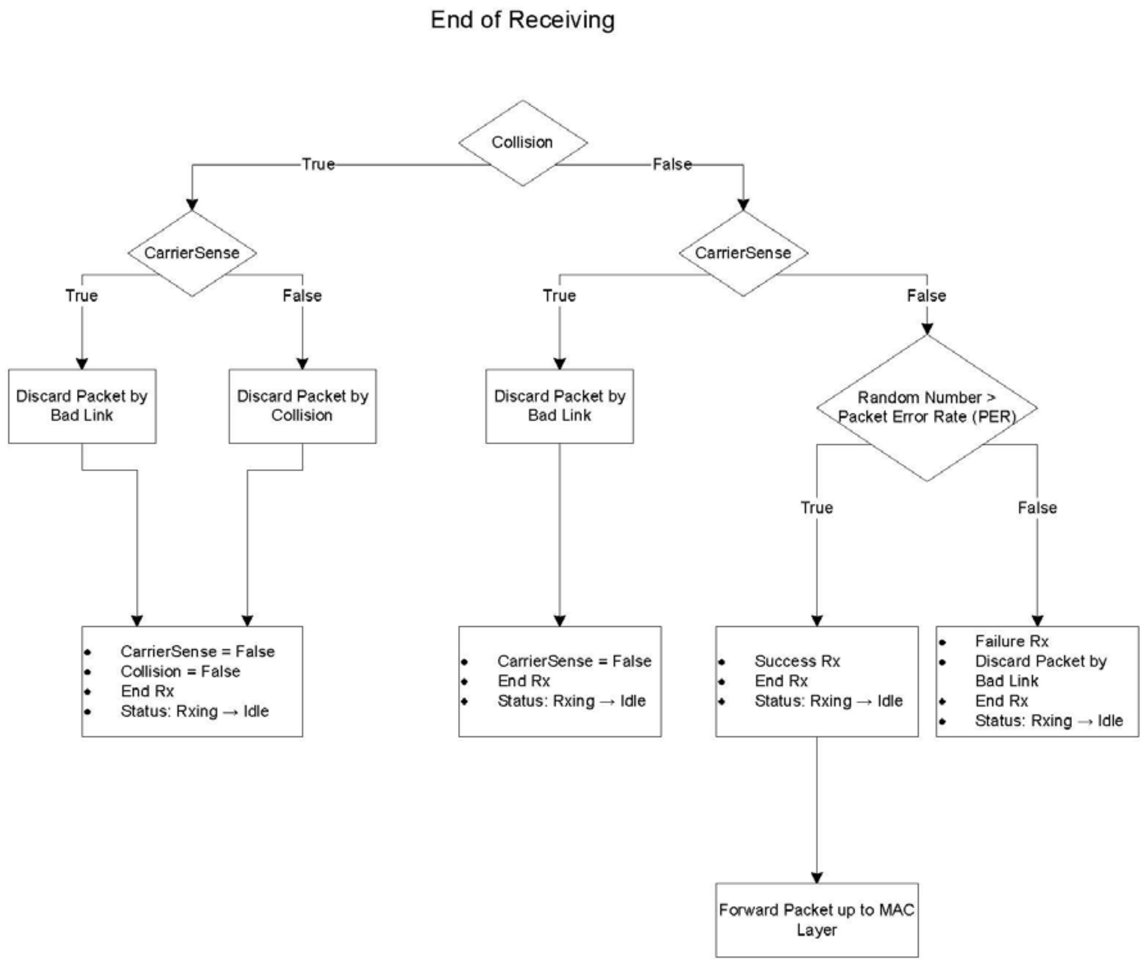

Figure A.2 The Procedure of the End Receiving in FER-Based Reception Model