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資訊科學與工程研究所

博 士 論 文

IEEE 802.11 多重速率無線網路的效能評估與改善

Performance Analysis and Improvements on
Multi-Rate IEEE 802.11 Wireless Networks

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中 華 民 國 九十八 年 一 月

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摘要

由於無線技術的進步,使得現今的無線設備能夠提供較高的傳輸速率,因而無線網路變得很受歡迎. 例如, IEEE 802.11n 能提供最高到 540 Mbps 的傳輸速率. 這些高傳輸速率都是藉由在網路實體層使用不同的調變技術而達到的. 當傳輸頻道的品質發生變化時,使用不同的調變技術或傳輸速率可改善網路的頻寬. 為了要讓無線設備能根據當時傳輸頻道的品質,使用最適當的傳輸速率,我們可用人工的或自動的方式來調整傳輸速率. 但如何自動調整傳輸速率,以往只有在格狀網路中有較多的研究,在 IEEE 802.11 中不但沒有規定,且在無線區域網路中所作的研究也很少.

在本論文中,我們首先針對 802.11 在多重速率無線區域網路提出 3 個問題,即(1)耗電量的管理效能不足(2)對使用不同傳輸速率的無線設備有不公平的頻道時間分配及(3)網路頻寬下降. 然後我們提出了一個封包排班方式,來改進這些問題.

在本論文的第二部份,我們提出了一個可用來評估 802.11 DCF 在多重速率無線區域網路中頻寬及封包延遲效能的模型.

最後,我們也介紹如何計算一個靜態多跳躍多重速率無線網路中路徑的頻寬,接下來,我們希望能找到一個較實際的無線使用者移動模式,這樣就能計算一個動態路徑的頻寬,進而能設計一個以頻寬為標準的路徑選擇方式.

論文中我們也藉由模擬的結果來驗證所提出的封包排班方式, 效能評估模型及路徑頻寬計算的正確性.

Performance Analysis and Improvements on Multi-Rate IEEE 802.11 Wireless Networks

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Abstract

Due to the availability of affordable devices that are capable of transmitting at high data rates, wireless LANs (WLANs) have become increasingly popular. For example, the IEEE 802.11n standards now can support data rates up to 540 Mbps. These high rates are achieved through new modulation schemes that are optimized for the channel conditions bringing about a dramatic increase in throughput performance. Since the choice of which modulation scheme to use depends on the current state of the transmission channel, newer wireless devices often support multiple modulation schemes, and hence multiple data rates, with mechanisms to switch between them. Users are given the option to either select an operational data rate manually or to let the device automatically choose the most appropriate data rate to match the prevailing conditions. Although automatic rate adaption protocols have been studied widely for cellular networks, there have been relatively few proposals for WLANs.

In this dissertation, we first showed 3 problems of the 802.11-based WLANs in which the wireless devices have the multi-rate capability: (1) the problem of power management inefficiency; (2) the problem of unfair channel time allocations; and (3) the problem of degraded network throughput. We then proposed a scheduling mechanism, called the Shortest Time First Scheduling, to improve these problems.

In the second part of this dissertation, an analytical model, called the Rate-Adaptive Markov Chains, was proposed to study the saturation throughput and delay performance of a WLAN in which the mobile hosts have the multi-rate and automatic rate adaption capability.

We also showed how to evaluate the throughput of a path for stationary STAs in

multi-rate multi-hop ad hoc networks. In the future, we hope to develop a practical user mobility model such that the expected throughput of a dynamic route can be evaluated. Then, a routing protocol to select the most throughput efficient path from all possible paths can be designed.

Simulations are also provided to verify the performance of the packet scheduling mechanism, the correctness of the analytical model and the mechanism used to evaluate path throughput.

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Finally, I would like to dedicate this dissertation to my parents, my wife, Jia-Huie, and two sons, Jhih-Sian and Jhih-Cing.

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Chapter 1

Introduction

In recent years, the family of IEEE 802.11 protocols has become the most popular access method for WLANs. With wireless access, a mobile user can connect its wireless network-equipped laptop or other devices to the network anywhere and anytime without cumbersome cables or wires. IEEE 802.11 WLANs can operate either in infrastructure mode or in ad hoc mode. In the ad hoc configuration, wireless stations (STAs) are brought together to form a network "on the fly". There is no structure to the network; there are no fixed points; and usually every STA is within the communication range of every other STA in the network. When configured in infrastructure mode, the WLAN consists of at least one access point (AP) connected to the wired network and a number of wireless STAs. The AP provides a local relay function for the network. All STAs in the network communicate with the AP and no longer communicate with each other directly.

In 802.11 protocols, the fundamental medium access method is called DCF (Distributed Coordination Function), a form of carrier sense multiple access with collision avoidance (CSMA/CA). The DCF first checks to see if the radio link is free before transmitting and then initiates a random backoff procedure to avoid collisions. In some circumstances, the DCF may use the RTS (Request To Send) and CTS (Clear To Send) technique to further prevent collisions. The saturation throughput performance of the DCF on the condition that all hosts in the network use the same transmission rate was analyzed in [1, 2, 3, 4, 5]. The 802.11 protocols also define an optional Point Coordination Function (PCF) to enable the transmissions of time-sensitive information. In PCF, a point coordinator (PC) within the access point controls which mobile hosts can transmit during any given period of time. This makes it possible to effectively support information flows that have stiffer synchronization requirements. The throughput performance of the PCF was studied in [5, 6].

Generally, the problems found on 802.11 wireless networks include:

1. The transmission ranges are limited, and the media are unreliable.

2. The network topologies are dynamic.
3. Signal transmissions may be interfered by outside sources.
4. There are hidden/exposed terminals.
5. The battery lives of wireless devices are limited.
6. The network bandwidth is lower than that of wired networks.
7. The network security is poorer than its wired counterpart.
8. The wireless links are time varying and asymmetric.
9. There are long-term/short-term fairness problems.

Therefore, the research issues from the physical to the application layer on the 802.11 wireless networks include:

1. Physical Layer
   – How to reduce the effects of interferences ?
2. MAC Layer
   – How to analyze and improve the performance of the DCF and PCF ?
3. Network Layer
   – How to maintain the routing tables in the context of highly mobile environments (multi-hop routing) ?
4. Transport Layer
   – How to enhance the TCP performance over the multi-hop ad hoc networks ?
5. Application Layer
   – How to satisfy application requirements (delay, throughput) ?
   – How can the application adapt to the channel ?
   – How to provide a more secure 802.11 network environment ?
6. Resource Conservation
   – How to minimize power consumptions of the wireless devices ?
   – How to enhance network bandwidth ?
   – How to handle the failures of the mobile devices ?
7. Interoperability with other relevant technologies, such as the bluetooth, ultrawideband, 3G cellular networks, and 802.16 broadband wireless networks.

In this dissertation, we will first propose a packet scheduling mechanism to improve the power efficiency, throughput, and fairness in channel time allocations of an 802.11 ad hoc network in which the wireless devices may use different rates for transmissions. We then present an analytical model to analyze the performance of the DCF in the multi-rate ad hoc networks. Finally, a mechanism used to evaluate the throughput of a stationary path in which wireless devices will use different transmission rates is proposed. Simulation results are also provided to verify the benefits and correctness of the proposed mechanisms.

Chapter 2

The 802.11 Basics

In this chapter, we will introduce some of the basic ideas of the IEEE 802.11 protocols.

2.1 The IEEE 802.11 Random Backoff Procedure

In DCF, collision avoidance is achieved by using a random backoff procedure. An STA that senses the channel to be busy must wait until the medium is free. Since multiple stations could have been waiting for accessing the medium, there is a high probability of collisions immediately after the medium becomes free. In order to reduce collisions, an STA must generate a random backoff time (a random integer times a fixed time interval called the SlotTime), which is an additional interval beyond the DIFS (DCF Inter Frame Space) time that the STA must wait before it can transmit again. In 802.11, this random integer is selected uniformly between 0 and W-1. The value of W is called the Contention Window size, and it depends on the number of previous transmission failures for a packet. At the first transmission attempt, W is set to the initial value of W_{min} (the minimum contention window size). After each unsuccessful transmission, W is doubled, up to the maximum value of W_{max}. After a successful transmission, W will be reset to W_{min} for the next packet. For example, the values of W_{min} and W_{max} are 32 and 1024, respectively, in 802.11b [7]. If multiple STAs are in the backoff procedure simultaneously, the STA that selects the smallest backoff time transmits first. A simple example of the backoff mechanism is shown in Fig. 1.1, in which only one STA is allowed to transmit, all other STAs will freeze their backoff counters.

2.2 The Multi-Rate Support in IEEE 802.11

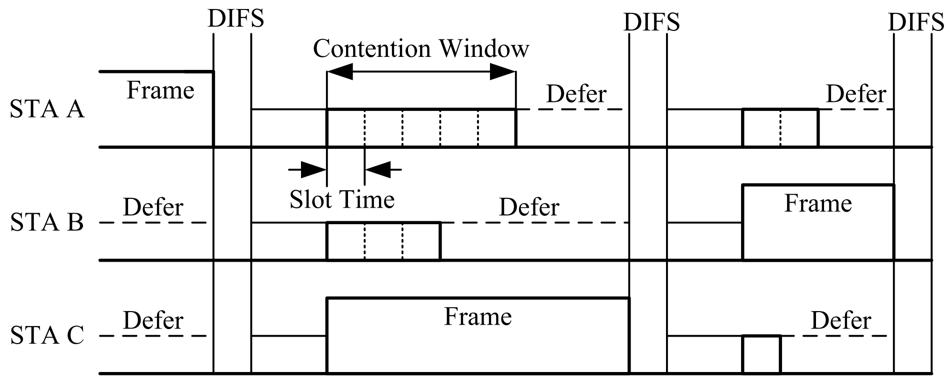

Figure 2.1: IEEE 802.11 Backoff mechanism.

Because of signal fading, transmission interference, shadowing, path loss, and user mobility, wireless channels have time varying characteristics. Therefore different mobile STAs may perceive different channel qualities at the same time. In order to obtain optimum throughput, STAs in the network need to use different transmission rates for different channel qualities [8], namely: using high or low transmission rate for good (high signal to noise ratio or SNR) or bad channel condition can have better link throughput. Currently most protocols, including IEEE 802.11b, 802.11a, 802.11g, and HiperLAN-II, have this multi-rate support, which is achieved via different modulation and coding schemes at the Physical layer. The 802.11 standards propose the following rules to ensure the interoperability of all devices which support multi-rate capable physical layers.

1. All control frames must be transmitted at one of the rates in the so-called BSSBasicRateSet[1] to ensure that they will be understood by all STAs in the network.
2. All multicast and broadcast frames must be transmitted at one of the rates in the BSSBasicRateSet.
3. All data frames must be sent at the data rate chosen by the rate adaptation algorithm (if the rate is supported).

[1] The list of data rates that must be supported by any STA wishing to join a network.

4. No STA in the network is allowed to send messages with a rate greater than the highest rate in the so-called OperationalRateSet[2].
5. Control Response frames (e.g., CTS or ACK) must be sent at the same rate as the previous received Control frame if that rate is part of the mandatory rates. Otherwise they have to be sent at the highest possible rate in the BSSBasicRateSet.

In [9], the authors analyzed the DCF performance for finite load STAs in a multi-rate environment in which different STAs may use different transmission rates, but each STA still only uses the same rate for all of its transmissions.

2.3 The Automatic Rate Adaptation

Rate adaptation is the process of dynamically switching data rates to match the wireless channel quality, with the goal of selecting the rate that will give the optimum throughput for the given channel quality. While this rate adaptation algorithm is a critical component for link performance, it is unspecified in 802.11, and few rate adaptation techniques have been designed for WLANs in the literature. We summarize some important works below. In [10], the authors proposed the Auto Rate Fallback (ARF) protocol, which is the first published rate adaptation algorithm for 802.11 and has been used in Lucent's WaveLAN-II devices. In ARF, the sender attempts to use a higher rate after 10 consecutive successes at a given rate and switches to a lower rate after 2 successive losses. Although ARF can provide a performance gain over the single rate IEEE 802.11 under most channel conditions, it can not adapt rates efficiently for fast or slowly changing channels [11]. A number of

[2] The set of data rates that an STA may use for communication with other STAs in a BSS.

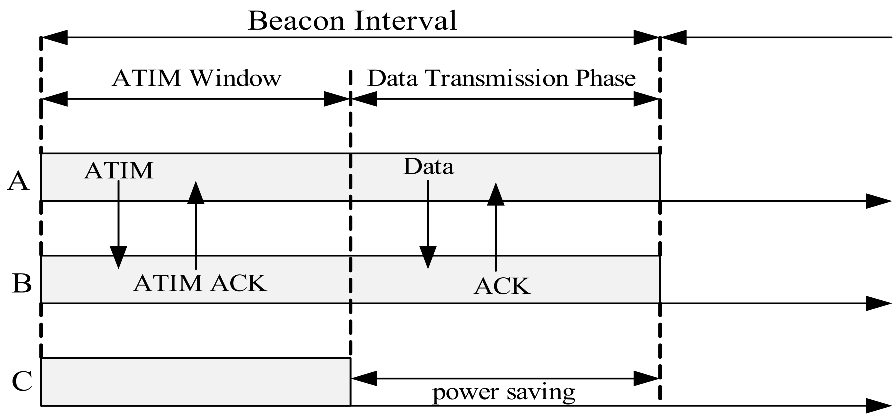

Figure 2.2: The 802.11 Power Saving Mechanism.

modified ARF protocols are therefore proposed [11, 12]. In RBAR [13], a pair of RTS/CTS frames is exchanged between the sender and the receiver before the start of each data transmission. Based on the signal strength of the received RTS frame, the receiver will select the most appropriate rate for the sender to use in data transmission. The selected rate is then sent back to the sender through the CTS frame. The results from [13] show that RBAR does have higher rate adaptation capability than ARF. But the problems with RBAR are:

1. A RTS/CTS frame exchange is always needed even no hidden hosts are present.
2. The formats of the RTS/CTS frames need to be modified, so it can not be used in existing networks.

Other works on rate control to improve energy efficiency and/or network throughput are in [31, 32, 33, 34, 35, 36].

2.4 The IEEE 802.11 Power Saving Mechanism

In WLANs, battery power is an unavoidable issue that must be dealt with. In order to save power, 802.11 defines a MAC-layer Power Saving Mechanism (802.11 PSM) that allows a wireless STA to go from the active state to doze or power saving state when the STA is not involved in any data transmissions [7]. In the infrastructure configuration of a WLAN, the AP will keep track of all STAs that are in power-saving state and buffer frames addressed to these STAs. These frames are kept until the STAs request them to be sent or discarded if they are not requested for a certain period of time. While in the case of ad hoc configuration, time is divided into Beacon Intervals and each Beacon Interval contains an ATIM (Ad Hoc Traffic Indication Message) Window followed by the Data Transmission Phase. The ATIM Window is used as the common awake period for all participating STAs to announce their traffic through ATIM frame transmissions. After the ATIM Window finishes, STAs that successfully send or receive ATIM frames must remain in the active state, and STAs can switch to power-saving state if they are not involved in any traffic announcements till the beginning of next ATIM Window. Actual data transfers occur in the Data Transmission Phase, and the normal DCF (Distributed Coordination Function) access procedure is used while sharing the transmission medium among the active STAs. Any STA that completes the ATIM frame transmission in the ATIM Window but fails to send data packet in the Data Transmission Phase will try to initiate another traffic announcement in the next ATIM Window. This Power Saving Mechanism can be exemplified by the diagram in Fig. 1.2.

In Fig. 1.2, STA A announces a buffered packet for B using an ATIM frame. STA B replies by sending an ATIM-ACK, and both A and B stay awake during the entire Beacon Interval. The actual data transmission from A to B is completed during the Beacon Interval. Since C does not have any packet to send or receive, it dozes after the ATIM window. In addition to the 802.11 PSM, a number of power saving methods [14, 15] covering all protocol layers from Physical to the Application layer have also been proposed in the literature, and a system-level power-saving methodology for heterogeneous wireless networks is in [16].

Chapter 3

The Shortest Time First Scheduling Mechanism

3.1 The Problem of the IEEE 802.11 PSM

As we said in Sec. 1.2, wireless STAs need to use different rates for different channel qualities. But when the 802.11 PSM is enabled in such a multiple rate ad hoc environment, we observe a problem of power management inefficiency which can be exemplified in Fig. 2.1. In this example, we assume there are 16 STAs in the network, 8 of which are transmitters[3], and 8 of which are receivers. Each transmitter has only one packet to send to its receiver and all data packets are equal in length. In those transmitters, 4 of them are fast STAs, and the other 4 are slow STAs. Since fast (slow) STAs will use less (more) time in sending packets, the packets transmitted by fast (slow) STAs are represented by narrow (wide) rectangles in Fig. 2.1. According to the operations of 802.11 PSM, these transmitters must first announce their traffic in the ATIM Window and then use DCF to contend for the channel in the Data Transmission Phase. In the worst case, it may happen that all slow transmitters win the channel contentions before any fast transmitter has a chance to send data packet. Therefore as shown in the upper half of Fig. 2.1, the numbers of STAs that must stay in the active/power-saving state in the first, second, and third Data Transmission

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[3] In this dissertation, a transmitter is a wireless STA that only transmit, not receive data packets.

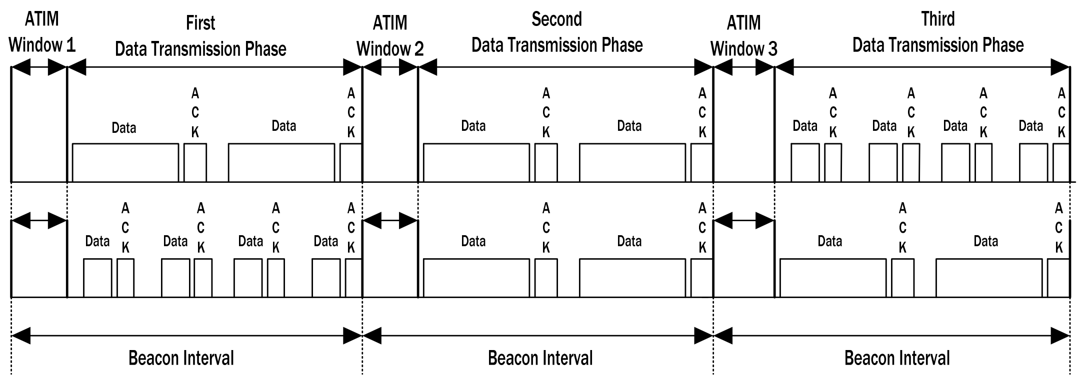

Figure 3.1: The worst-case and best-case scenarios of power management in an 802.11 multiple rate ad hoc network.

Phases are 16/0, 12/4, and 8/8, respectively. That is, 4 of the 16 STAs must stay in the active state for 2 Beacon Intervals, and 8 STAs must remain active for all of the 3 Beacon Intervals. In order to save power, we will propose a scheduling mechanism called STFS (Shortest Time First Scheduling) in this dissertation so that the packets transmitted on the channel can be as shown in the lower half of Fig. 2.1. This scheduling mechanism has the characteristic that it will schedule all fast transmissions or transmissions using less channel time to transmit before any of the slow STAs are allowed to send packet in every Data Transmission Phase. By scheduling in this way, more STAs can complete their data transmissions earlier and then go to power-saving state to conserve energy. Now the numbers of active/power-saving STAs are only 16/0, 8/8, and 4/12 in Data Transmission Phases 1, 2, and 3, respectively, the total power consumptions of these STAs are thus minimized.

3.2 The Problem of Unfair Channel Time Allocations

In addition to the problem of power management inefficiency stated in Sec. 2.1, there is a performance anomaly for ad hoc networks with STAs using different

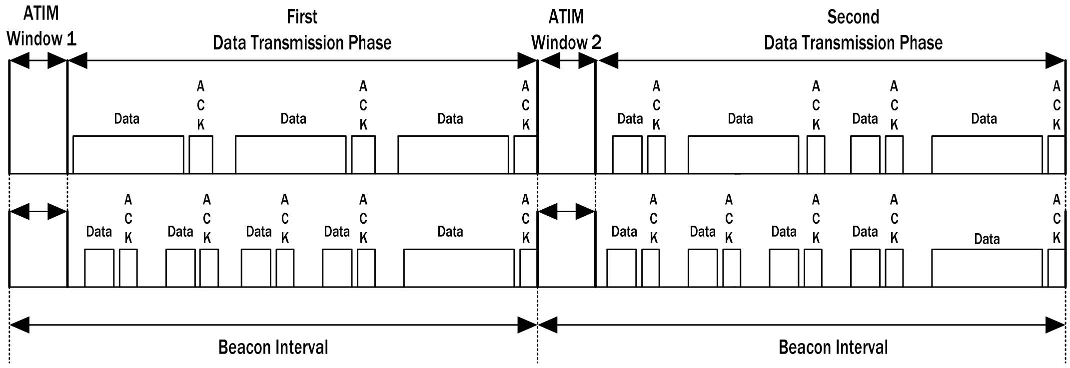

Figure 3.2: The numbers of packets that are actually transmitted in each Data Transmission Phase for 802.11 PSM (the upper half) and STFS (the lower half) in an 802.11 multiple rate ad hoc network.

transmission rates [17]. This anomaly is due to the fact that 802.11 is fair only on station or packet level but not on the temporal level so that all STAs in the network have the same saturation throughput. That is, this packet level fairness makes fast STAs be allocated much less channel time than that allocated to the slow STAs. The authors in [9] proposed a model to investigate this anomaly and mitigated the unfair channel time allocations between different-rate STAs by using larger minimum contention window sizes or smaller packet sizes for slow STAs. The problem with these methods is that the saturation throughput of the slow STAs will be degraded. Since the Data Transmission Phase in a Beacon Interval has a fixed time interval, this time interval may be too short for all active transmitters to complete their data transmissions. This may happen when there are too many active transmitters contending for the channel in the same Data Transmission Phase or when the total amount of time needed for all active transmissions is longer than the time interval of the Data Transmission Phase. When either of these situations occurs, our scheduling mechanism can provide higher network throughput and allocate more channel time to fast STAs, as illustrated with the example in Fig. 3.2. We assume in this example that:

1. The number of transmitters that can complete the traffic announcement in

each ATIM Window is 10, of which 4 are fast and 6 are slow.

2. Each transmitter always has a packet ready to transmit to its receiver.
3. The link rate used by fast/slow transmitters is $2r/r$ Mbps.
4. The packet size at the physical layer is m bits.
5. The length of the Data Transmission Phase is too short to accommodate all 10 data transmissions.

Fig. 3.2 shows a possible data transmission by 802.11 PSM and the transmissions scheduled by our STFS in 2 Beacon Intervals. As shown in this figure, the numbers of packets that actually transmitted by fast/slow transmitters in Data Transmission Phase 1 (2) are 0/3 (2/2) for 802.11 PSM and 4/1 (4/1) for STFS. By scheduling fast transmissions to proceed first, STFS can accommodate more packets in every Data Transmission Phase. The total number of packets transmitted by STFS in these 2 Beacon Intervals is greater than that transmitted by 802.11 PSM, thus STFS can deliver higher network throughput than 802.11 PSM can provide. The total amount of channel time, in μs, used by all fast (slow) STAs to transmit data packets (not including the time used by ACK transmissions) is defined as $\Sigma_i\ n_i \times m/2r$ ($\Sigma_i\ n_i \times m/2r$), where n_i is the number of data packets actually transmitted in the ith Beacon Interval. Therefore, in Fig. 2.2, the channel time allocated to all fast (slow) transmitters is $0 \times m/2r + 2 \times m/2r = m/r$ ($3 \times m/r + 2 \times m/r = 5m/r$) for 802.11 PSM and $4 \times m/2r + 4 \times m/2r = 4m/r$ ($1 \times m/r + 1 \times m/r = 2m/r$) for STFS. The total time allocated to all fast transmitters is thus increased from m/r to $4m/r$, while that allocated to slow transmitters is slightly decreased from $5m/r$ to $2m/r$, therefore STFS can offer fast transmitters more opportunities to send packets than 802.11 PSM. In the example of Fig. 2.1, we assume each transmitter only has a specified number of data packets to send, therefore after a transmitter completes all its data transmissions, it will go to the doze mode; that is, the number of active transmitters in each Beacon

Interval may decrease over time. By scheduling fast transmissions to proceed first, STFS can make this decrease more significant, so more power can be saved, but neither network throughput nor the fairness problem are improved in this case. While in the example of Fig. 2.2, each transmitter in the network always has a packet ready to be sent, so the number of active transmitters will remain almost the same in every Beacon Interval (because the ATIM Window has a fixed time interval). If the Data Transmission Phase is too short to accommodate all active transmissions, not all active transmitters have chances to send their packets. By scheduling fast transmissions first, more data transmissions and more fast transmissions are allowed in every Beacon Interval, the network throughput and the fairness problem, not the total power consumptions, are thus improved.

3.3 Proposed Scheduling Mechanism

In STFS, we assume:

1. The WLAN is configured in its ad hoc mode.
2. An ideal channel condition without packet losses is considered.
3. The Beacon Intervals begin and end approximately at the same time at all STAs, so the problem of time synchronization is not considered.
4. Each STA in the network can support k data rates, $r_1 > r_2 > \bullet \bullet \bullet > r_k$, and has implemented an automatic rate selection protocol such as the RBAR in [13], which enables a receiver to select the most appropriate rate for its sender to use in the Data Transmission Phase.
5. The data packets transmitted by all STAs are equal in length so the time required to transmit a packet is determined by its transmission rate.

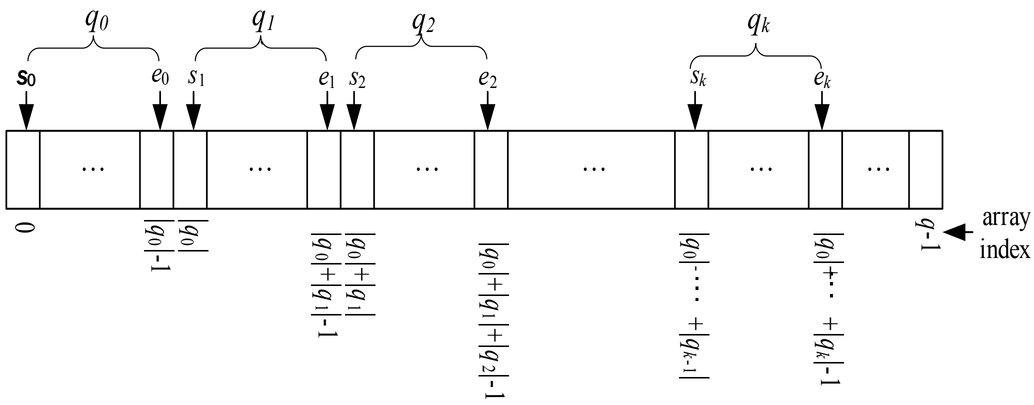

Figure 3.3: The configuration of k+1 queues in the scheduling array.

6. The promiscuous mode of the wireless interface is enabled so that the interface can intercept and read each network packet that arrives in its entirety.

As we mentioned earlier, STFS will schedule all fast transmissions before any of the slow transmissions in every Beacon Interval. A major problem with this scheduling mechanism is starvation; that is, some of the slow STAs may have no chances to send packets when Data Transmission Phase can not accommodate all active transmissions. In order to achieve the goals of shortest time first and starvation prevention, we modify the packet formats of 2 control frames as follows:

1. The ATIM frame is extended with a 1-byte *aging* field.
2. The ATIM-ACK is modified to include 2 additional 1-byte fields, *aging* and *rate*.

The uses of these fields will be described in the following paragraph.

In addition to the above modifications, each STA in the network needs to maintain a local counter, *fc*. This counter has an initial value of 0. Whenever an STA has made a traffic announcement in an ATIM Window but fails to initiate transmission in the following Data Transmission Phase, *fc* is incremented by 1, otherwise *fc* is reset to 0. Before an ATIM frame is sent, the transmitter will copy the value of *fc* to the *aging* field of the frame. After an ATIM frame is received, the rate selected by the receiver is sent back to it's transmitter through the *rate* field of the ATIM-ACK. The contents of the field *aging* in ATIM-ACK are coming from the same field of the received ATIM frame.

For the purpose of deciding packet transmission order in every Data Transmission Phase, a scheduling array of size q and a number of $2 \times (k + 1)$[4] indexes, s_0, e_0, s_1, e_1, • • • , s_k, e_k, also need to be maintained by each STA in the network. The size of this array is such that it can accommodate at least $k + 1$ non-overlapping queues, q_0, q_1, • • • , and q_k; that is: $|q_0| + |q_1| + \cdots + |q_k| \leqq q$. The two ends, front and rear, of each q_i are pointed to by s_i and e_i, $0 \leqq i \leqq k$, respectively. The configuration of these queues in the array is shown in Fig. 2.3. Whenever an STA receives an ATIM-ACK, the STA will use the *DA*[5], *rate*, and *aging* fields of the frame to update its scheduling array as follows:

1. If *aging* > 0, the contents of *DA* will be put into $q0$.
2. If *aging* = 0 and *rate* = r_i, the contents of *DA* will be put into q_i, $1 \leqq i \leqq k$, that is, the addresses of all STAs with the local counter $fc = 0$ and using the same data rate will be put into the same queue in the scheduling array.

The order of the station addresses in queue q_i, $1 \leqq i \leqq k$, is decided by the order of ATIM-ACK receptions, while the order in q_0 is determined as follows: The address in *DA* of ATIM-ACK$_1$ will have a smaller index value in q_0 than that in *DA* of

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[4] Recall that k is the number of different rates supported by STAs in the network.

[5] The Destination Address field, which now contains the address of the STA that transmitted the ATIM frame.

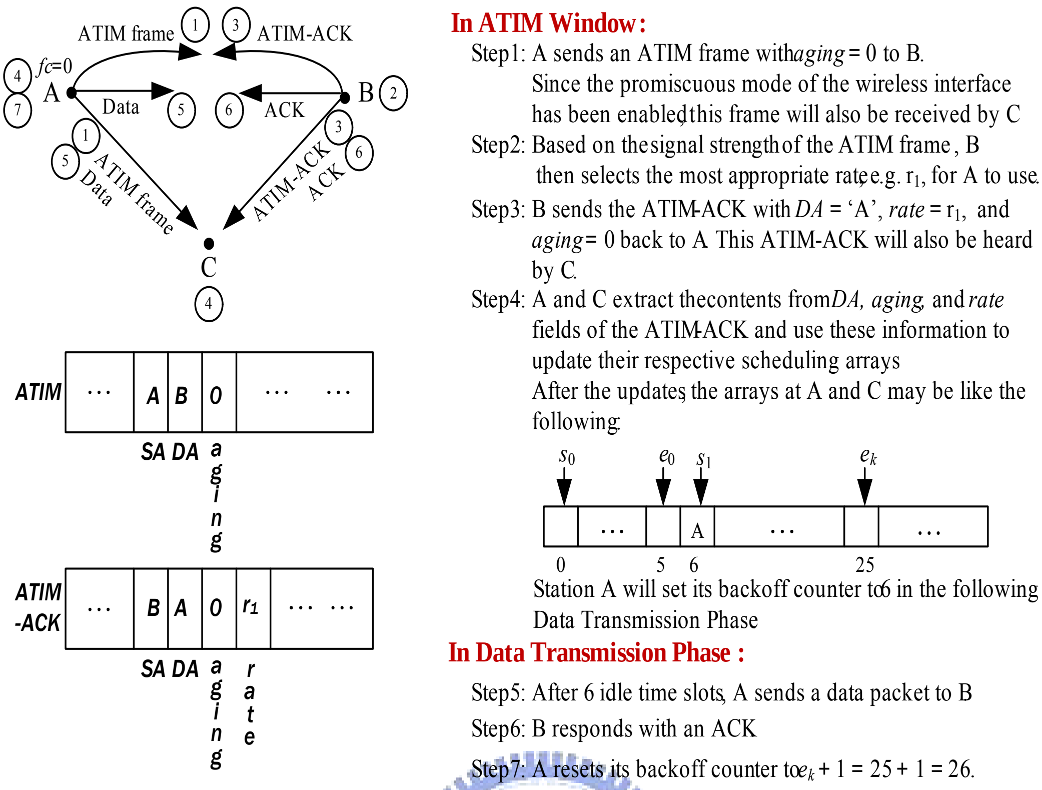


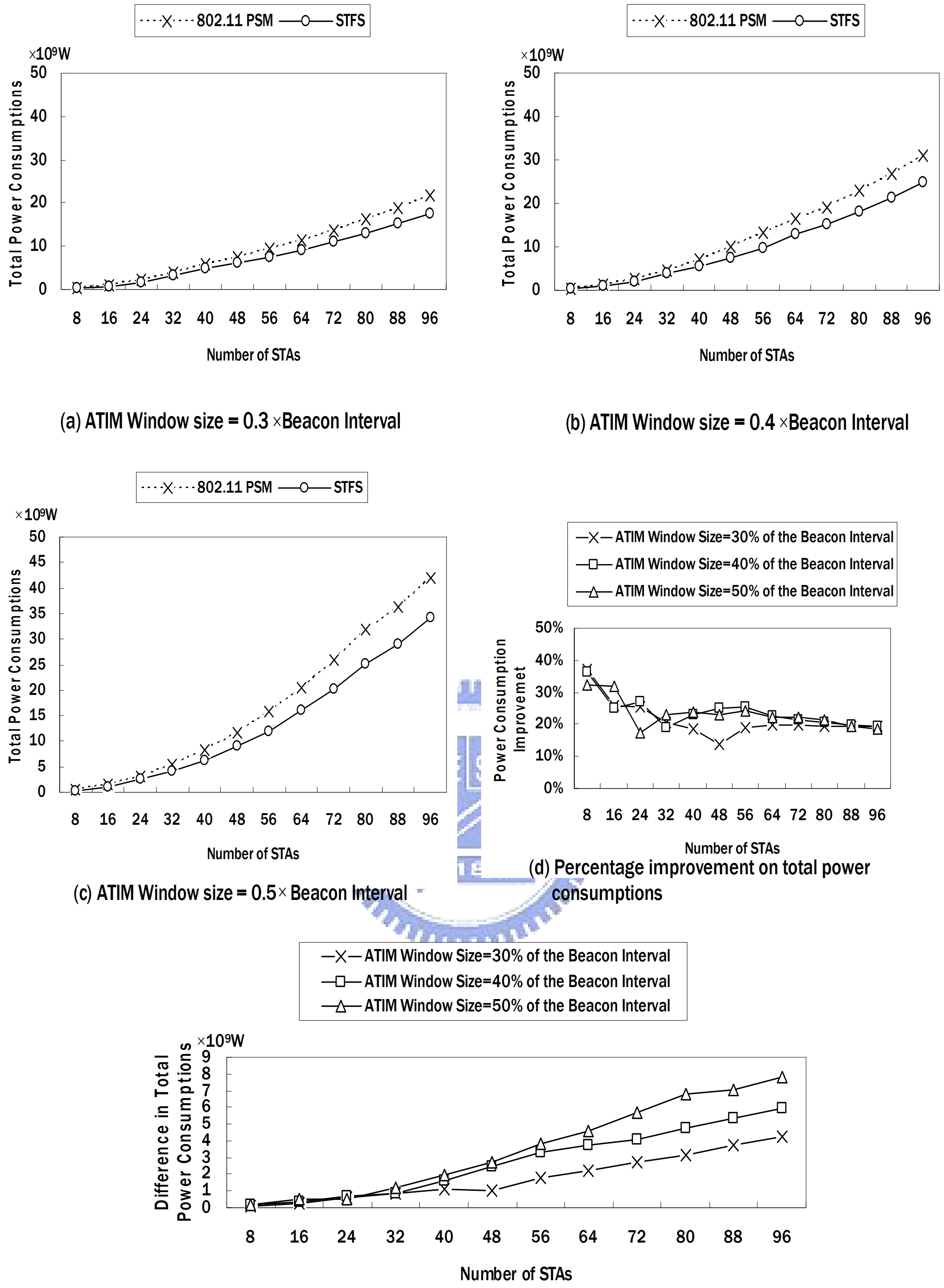
Figure 3.4: A simple STFS scheduling example.

ATIM-ACK$_2$ if (1) *aging* of ATIM-ACK$_1$ is larger than that of ATIM-ACK$_2$ or (2) *aging* of ATIM-ACK$_1$ is equal to that of ATIM-ACK$_2$ and *rate* of ATIM-ACK$_1$ is higher than that of ATIM-ACK$_2$ or (3) Both *aging* and *rate* of ATIM-ACK$_1$ are equal to those of ATIM-ACK$_2$, and ATIM-ACK$_1$ is received earlier than ATIM-ACK$_2$. For example, suppose an STA X receives 4 ATIM-ACKs with $DA =' A'$, $aging = 0$, and $rate = r_2$ at time t, $DA =' B'$, $aging = 0$, and $rate = r_2$ at time $t + 1$, $DA =' C'$, $aging = 1$, and $rate = r_1$ at time $t + 2$, and $DA =' D'$, $aging = 2$, and $rate = r_2$ at time $t + 3$. Then, in the scheduling array of STA X, the address of STA A will have a smaller index value in q_2 than that of STA B, and the address of STA D will have a smaller index value in q_0 than that of STA C. When ATIM Window finishes, the array index values will be used by those STAs whose addresses are recorded in the scheduling array to setup the backoff counters to be used in data transmissions. Therefore all

STAs whose addresses are in q_0 are permitted to send packets first, followed by the transmitters in q_1, and so on. Since the STAs whose addresses are in q_i will use a higher transmission rate than those whose addresses are in q_j , $1 \leqq i < j \leqq k$, the goal of shortest time first is achieved. Any STAs that had completed traffic announcements but failed to transmit data in the previous Beacon Interval(s) are recorded in q_0, so the starvation problem mentioned above is also solved. After a transmitter completes its data transmission, it will reset its backoff counter value to $e_k + 1$. This will give that transmitter chances to send multiple packets in the same Data Transmission Phase. After the current Beacon Interval terminates, the contents of the scheduling arrays maintained at all STAs are flushed to ensure the correct scheduling in the next Beacon Interval. A simple scheduling example of the STFS is shown in Fig. 2.4.

3.4 Performance of the STFS

We have developed a C++ based simulator to investigate the power consumption, channel usage, and throughput performance of the STFS and, for the purposes of comparison, the 802.11 PSM. Since the ATIM Window size will significantly affect the performance of 802.11 PSM [18, 19], we will vary that size to be 30%, 40%, and 50% of the Beacon Interval in each set of the simulations to see its effect on the performance of STFS. In this dissertation, we assume an STA will never be both a transmitter and a receiver at the same time. An 802.11b-based ad hoc network is particularly considered in our simulations, so the STAs in the network can support k = 4 different data rates, with $r1$ = 11.0 Mbps, $r2$ = 5.5 Mbps, $r3$ = 2.0 Mbps, and $r4$ = 1.0 Mbps. The rate used to send all control frames is 1 Mbps. In all simulations, we assume the numbers of transmitters that will use rate r_i, $1 \leqq i \leqq 4$, for data transmissions are equally distributed among all transmitters in the network. The size



(a) ATIM Window size = 0.3 ×Beacon Interval

(b) ATIM Window size = 0.4 ×Beacon Interval

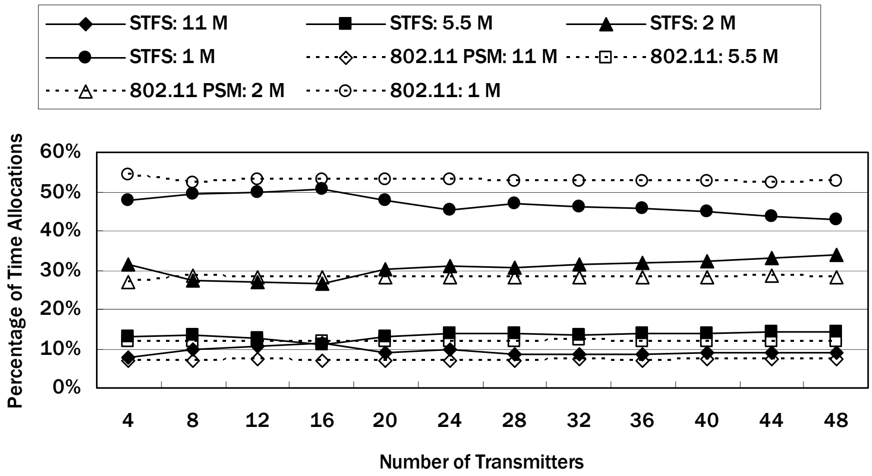
(c) ATIM Window size = 0.5× Beacon Interval

(d) Percentage improvement on total power consumptions

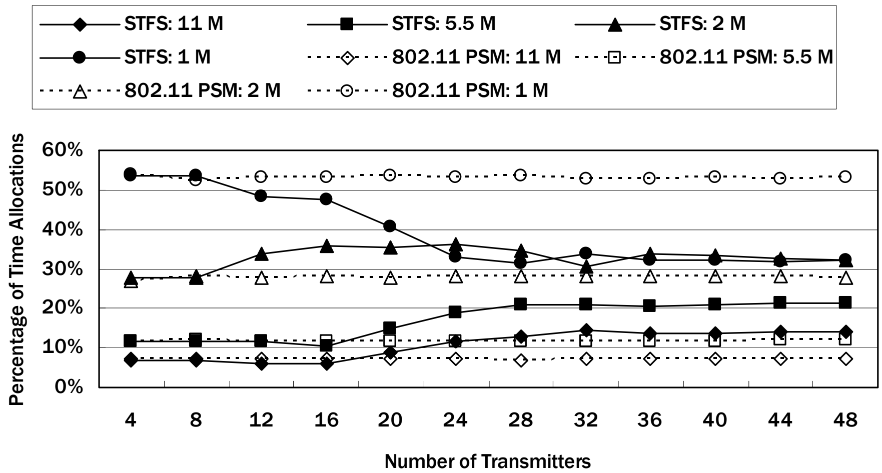
(e) The difference in total power consumptions between STFS and 802.11 PSM for ATIM Window of different sizes

Figure 3.5: Power consumption performances of STFS and 802.11 PSM with each transmitter having 1000 data packets to send.

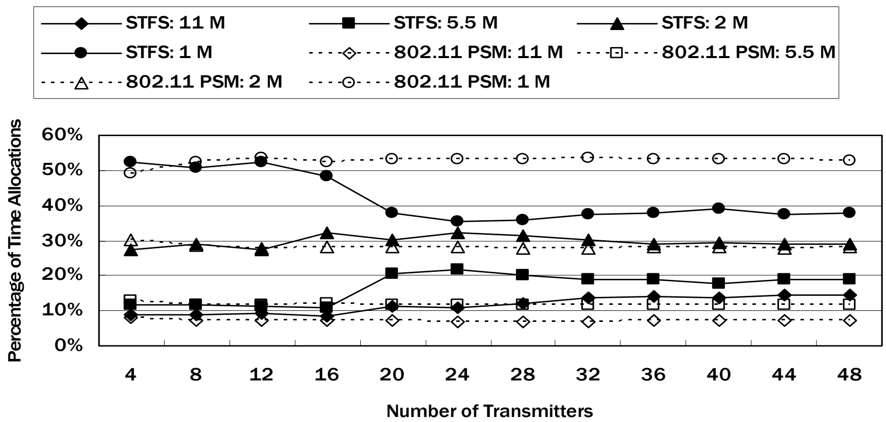
of the scheduling queue maintained at each STA is set to q = 63. The packet size at the MAC layer is fixed at 1024 bytes, and the lengths of the Beacon, ATIM, and



(a) ATIM Window size = 0.3×Beacon Interval

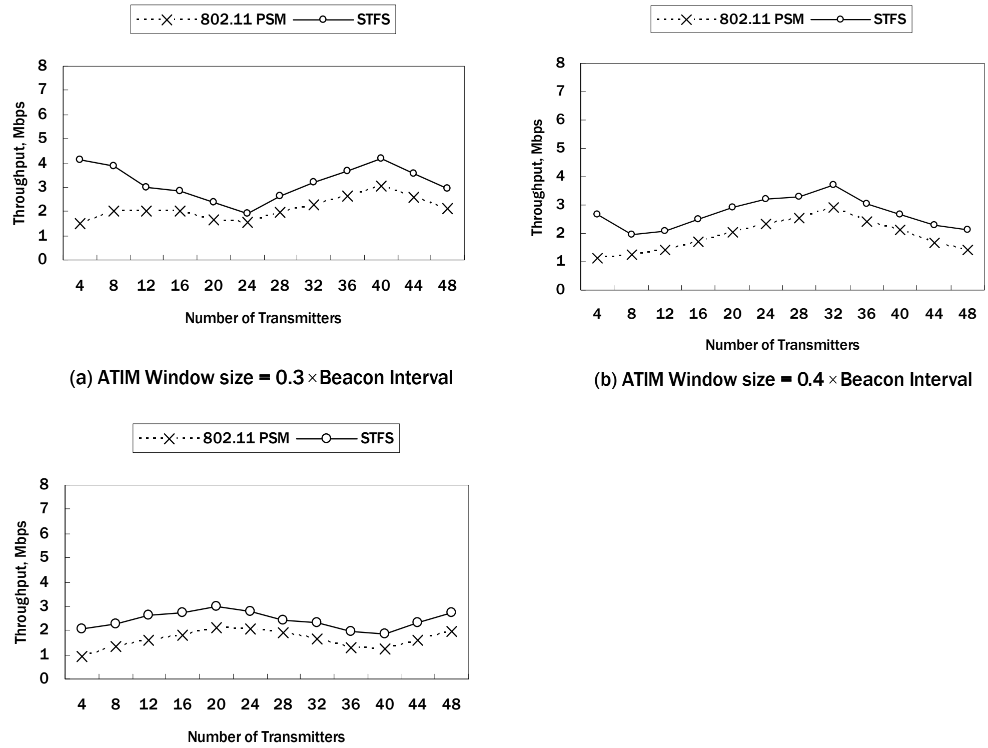


(b) ATIM Window size = 0.4×Beacon Interval



(c) ATIM Window size = 0.5× Beacon Interval

Figure 3.6: Percentage of total channel time allocated to STAs with different rates by STFS and 802.11 PSM in 1000 Beacon Intervals.



(a) ATIM Window size = 0.3 × Beacon Interval

(b) ATIM Window size = 0.4 × Beacon Interval

(c) ATIM Window size = 0.5 × Beacon Interval

Figure 3.7: The network throughput delivered by STFS and 802.11 PSM in 1000 Beacon Intervals.

ATIM-ACK frames for 802.11 PSM are 50, 28, and 14 bytes, respectively. The Beacon Interval is set to be 100 ms. For the energy model, a wireless STA will consume 1.65W, 1.4W, 1.15W, and 0.045Win the transmit, receive, idle, and the power-saving states, respectively [20, 21]. As in [22], the energy consumption for switching between awake and power-saving states is not considered in this dissertation. All simulation results are averages over 30 runs.

In the first set of simulations, the total power consumptions of all STAs are measured for the case in which one half of the STAs are transmitters and each transmitter has 1000 data packets to send to its receiver. The results are shown in Fig. 2.5(a) ~ (c). As we can see from the results, the total power consumed by all STAs in the network is less in STFS than in 802.11 PSM for all situations. The percentage improvement on total power consumptions, defined as $\frac{\text{TotalPowerComsumption}_{802.11\text{PSM}} - \text{TotalPowerComsumption}_{\text{STFS}}}{\text{TotalPowerComsumption}_{802.11\text{PSM}}}$, is shown in Fig. 2.5(d). We find a 20% to nearly 40% saving on energy is achieved by STFS. Finally, the results in Fig. 2.5(e) show that the savings on power consumption are more significant when the number of STAs in the network gets higher or the ATIM Window size becomes larger[6]. When these situations occur, more STAs will remain active in the same Data Transmission Phase, so the less chance they all can complete data transmissions. By scheduling fast transmissions first, STFS can send more packets in every Data Transmission Phase, therefore more STAs can complete their transmissions earlier and then go to power saving mode to conserve energy.

In the second set of simulations, we evaluate the percentages of total channel time used by STAs with different rates in 1000 Beacon Intervals, during which each transmitter always has a data packet ready to be sent. As defined in Sec. 2.2 of this dissertation, the total time, in μs, allocated to all transmitters with the data rate r_i, in Mbps, is $\sum n_j \bullet m/r_i$, where $1 \leqq i \leqq 4$ and $1 \leqq j \leqq 1000$, n_j is the number of data packets transmitted in the jth Beacon Interval using rate r_i, and m is the length, in bits, of the packet at the physical layer. The results are in Fig. 2.6. We can see that:

1. Transmitters with higher data rates, 11, 5.5, and 2 Mbps, can use more channel time in STFS than in 802.11 PSM, only the time allocated to transmitters with the lowest data rate, 1 Mpbs, is decreased.
2. The increases in time allocations to transmitters with higher rates are more noticeable when the number of transmitters in the network gets higher or the ATIM Window size becomes larger.

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[6] The larger the ATIM Window size, the shorter the length of the Data Transmission Phase for Beacon Interval with fixed length.

3. The total time allocated to the slowest transmitters is only decreased by less than 20% in all situations.

Therefore, no starvation problem occurs in our scheduling mechanism. These verify that the shortest time first scheduling mechanism can improve the fairness in channel time usages.

In the last set of experiments, we investigate the network throughput that can be delivered in 1000 Beacon Intervals by both STFS and 802.11 PSM. Each transmitter in the network also always has a data packet ready to transmit to its receiver. The results are in Fig. 2.7. From these results, we can say:

1. When the number of transmitters in the network is high, so that the Data transmission Phase can not accommodate all active transmissions, STFS can deliver higher throughput than 802.11 PSM, due to its nature of collision free and shortest time first scheduling.
2. When the number of transmitters is low, STFS still has better throughput performance, because it is collision free and offers chances for a transmitter to send multiple packets in a single Data Transmission Phase.

From the results of the above 3 sets of experiments, we can see that the STFS either can save more power than 802.11 PSM when STAs in the network have a specified number of packets to send or can deliver higher network throughput and offers more channel time to STAs with higher rates to send packets when STAs always have packets ready to be sent.

3.5 Concluding Remarks and Future Works

WLANs are usually designed for mobile applications. In mobile applications, battery power is one of the critical issues that must be dealt with. Due to limited battery power, various energy efficient protocols have been proposed to reduce wireless station's power consumptions in the literature. 802.11 addresses this power issue by allowing wireless stations to go into power-saving state at appropriate times to save power. However, this Power Saving Mechanism proposed by 802.11 has the problem of power management inefficiency when used in a multiple rate ad hoc network.

In this dissertation, a novel scheduling mechanism, STFS, is proposed to solve the above problem. The main idea of STFS is to schedule as many wireless stations to send packets as possible in every Beacon Interval so that they can complete their data transmissions earlier and then go to power-saving state to conserve energy.

Due to its nature of collision free, shortest time first scheduling, and possible multiple packet transmissions in a single Data Transmission Phase by a transmitter, STFS can improve network throughput and offer more opportunities to STAs with higher rates to send packets when transmitters always have packets ready to be sent in a multiple rate ad hoc network. Simulation results show that the improvements made by STFS are significant and obvious in all situations.

The following are some of the problems that may be considered as the future works on STFS:

1. How the STFS can be further extended with a parallel transmission mechanism to improve the spatial reuse of the WLANs?
2. How the STFS can be used in a multi-hop ad hoc network?

Chapter 4

Performance Analysis of the DCF in a Multi-Rate WLAN

In this chapter, we will propose a model, which we call Rate-Adaptive Markov Chains, to analyze the saturation throughput and delay performance of the DCF in an environment in which mobile STAs have multi-rate support and the capability of automatic rate adaptation. In our performance analysis, the following assumptions are made:

1. Each STA always has a packet ready for transmission so that the saturation throughput performance of the network can be evaluated.
2. The mobile STAs support α rates, $R_1 > R_2 > \bullet\bullet\bullet > R_\alpha$, and the maximum transmission range of R_i is d_i, $i = 1, 2, \bullet\bullet\bullet, \alpha$. Since there exists a tradeoff between rate and range, the following relations hold for these ranges: $0 < d_1 < d_2 < \bullet\bullet\bullet < d_\alpha$.
3. The STAs in the network follow the ARF protocol to perform rate switching.
4. The wireless channel quality depends only on the distance between a sender and its receiver. That is, in addition to the packet collisions, a transmission will fail only when the maximum transmission range at a given rate is exceeded.

Therefore according to the operations of ARF, the relationships between the rates R that a sender may use to communicate with its receiver and its distance d to the receiver are:

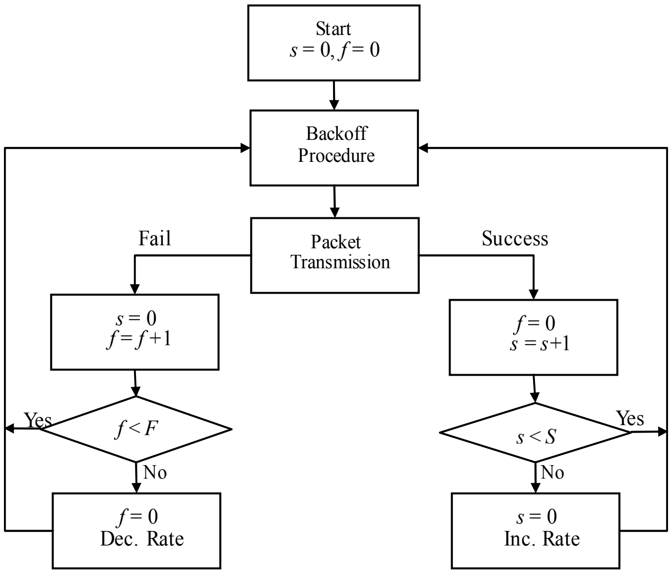


Figure 4.1: The general architecture of the Rate-Adaptive Markov Chain.

$$R = \begin{cases} R_1, R_2, \cdots, R_k & \text{if } 0 \le d < d_1 \\ R_{i-1}, R_i, \cdots, R_k & \text{if } d_{i-1} \le d < d_i \text{ and } 2 \le i \le k \end{cases} \quad (3.1)$$

The first relation in Eq. (3.1) indicates that a sender will use all supported rates to send packets when d is in the range between 0 and d_1. The second relation in Eq. (3.1) indicates that the sender may try to use the R_{i-1} for transmissions when $d_{i-1} < d \leqq d_i$, but such transmissions will always fail because this is out of the transmission range.

Because of user mobility, the distance between a sender and its receiver will change with time. We assume that the moving speed is at most a few meters per second for any pedestrian. Therefore, the wireless channel is considered as a slowly changing medium in our analysis.

Our model is based on the ones proposed in [2, 3] and extended with the ARF protocol. A general architecture of this model is shown in Fig. 3.1, in which $s = f$ is

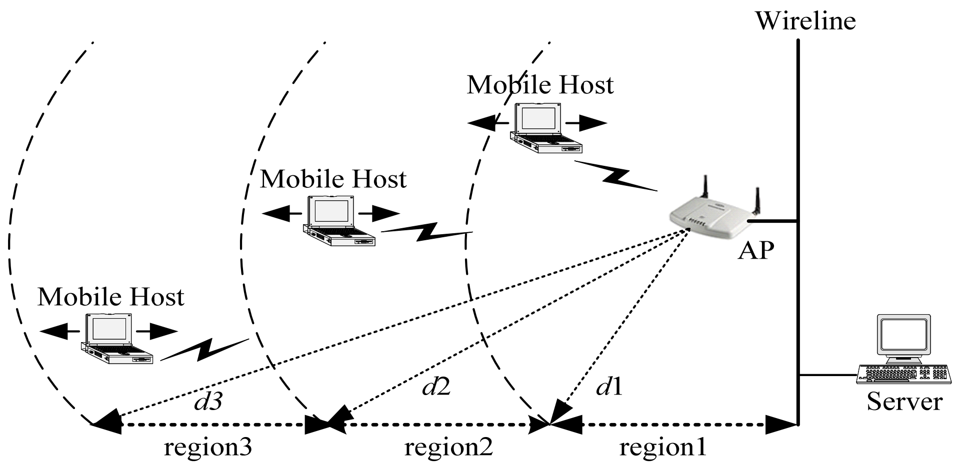


Figure 4.2: The network environment considered in analysis and simulations.

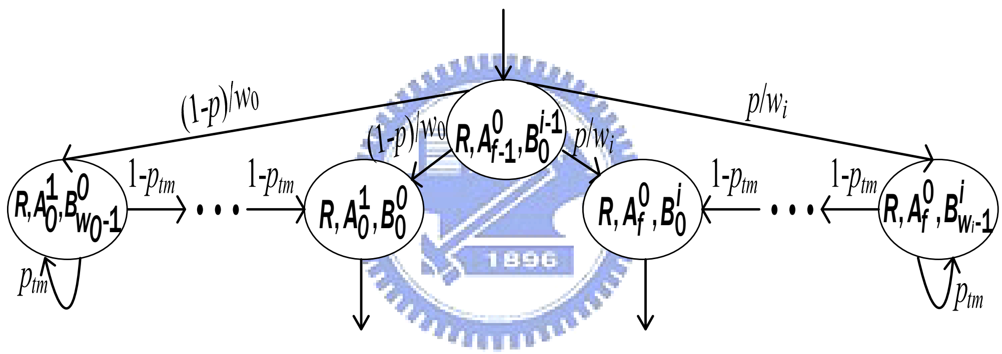


Figure 4.3: An example of the state transitions in the Backoff stages of the Rate Adaptive Markov Chains.

the current number of successes/losses and *S*/*F* is the maximum number of consecutive successes/losses before changing rates. To the best of our knowledge, we are the first to propose an analytical model that combines both 802.11 DCF and ARF.

4.1 The Rate-Adaptive Markov Chains

In this section we will present the Rate-Adaptive Markov Chains and show how to use them to evaluate the saturation throughput of the DCF for a given number of

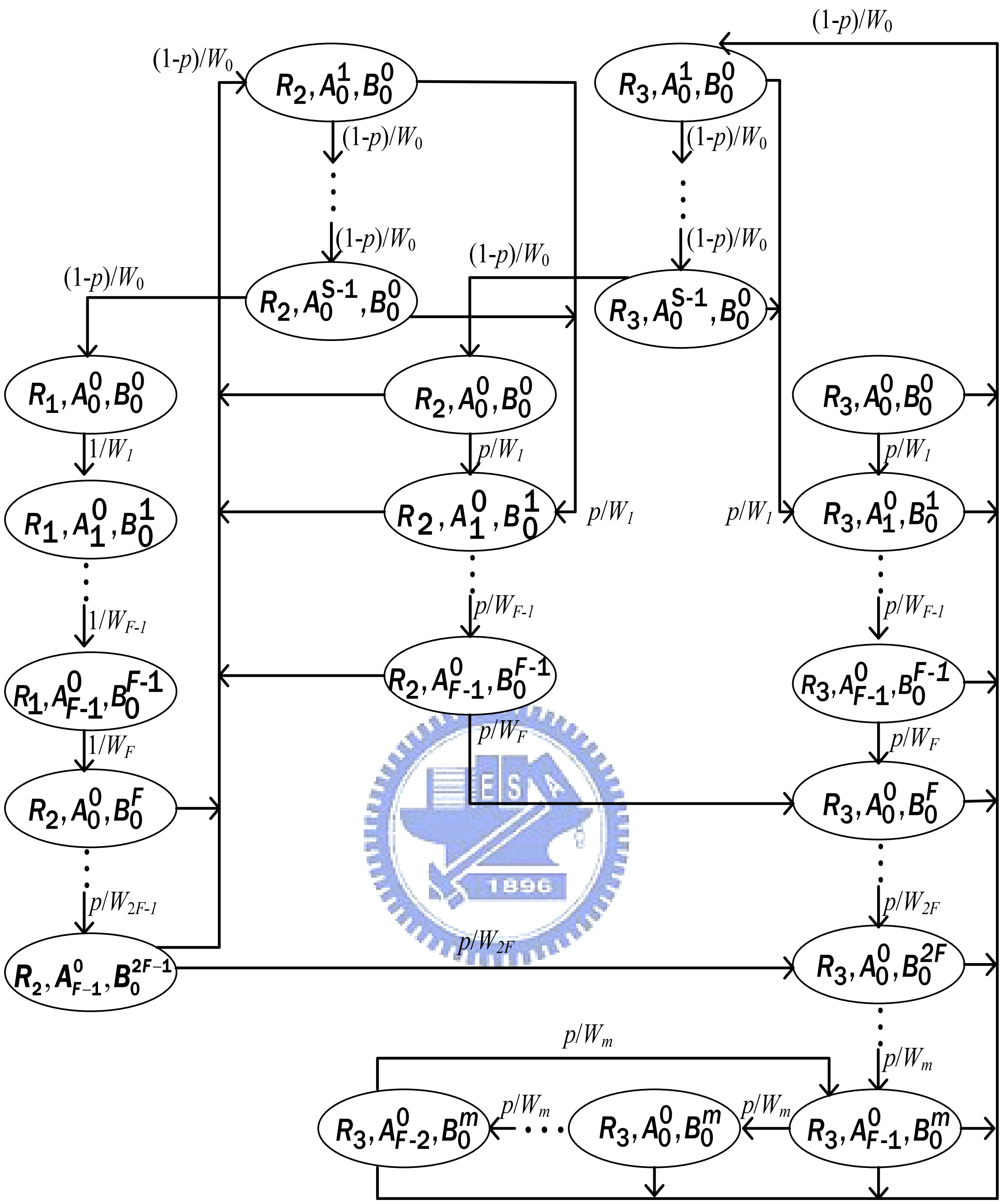


Figure 4.4: State transitions between transmission states in region1 of the AP.

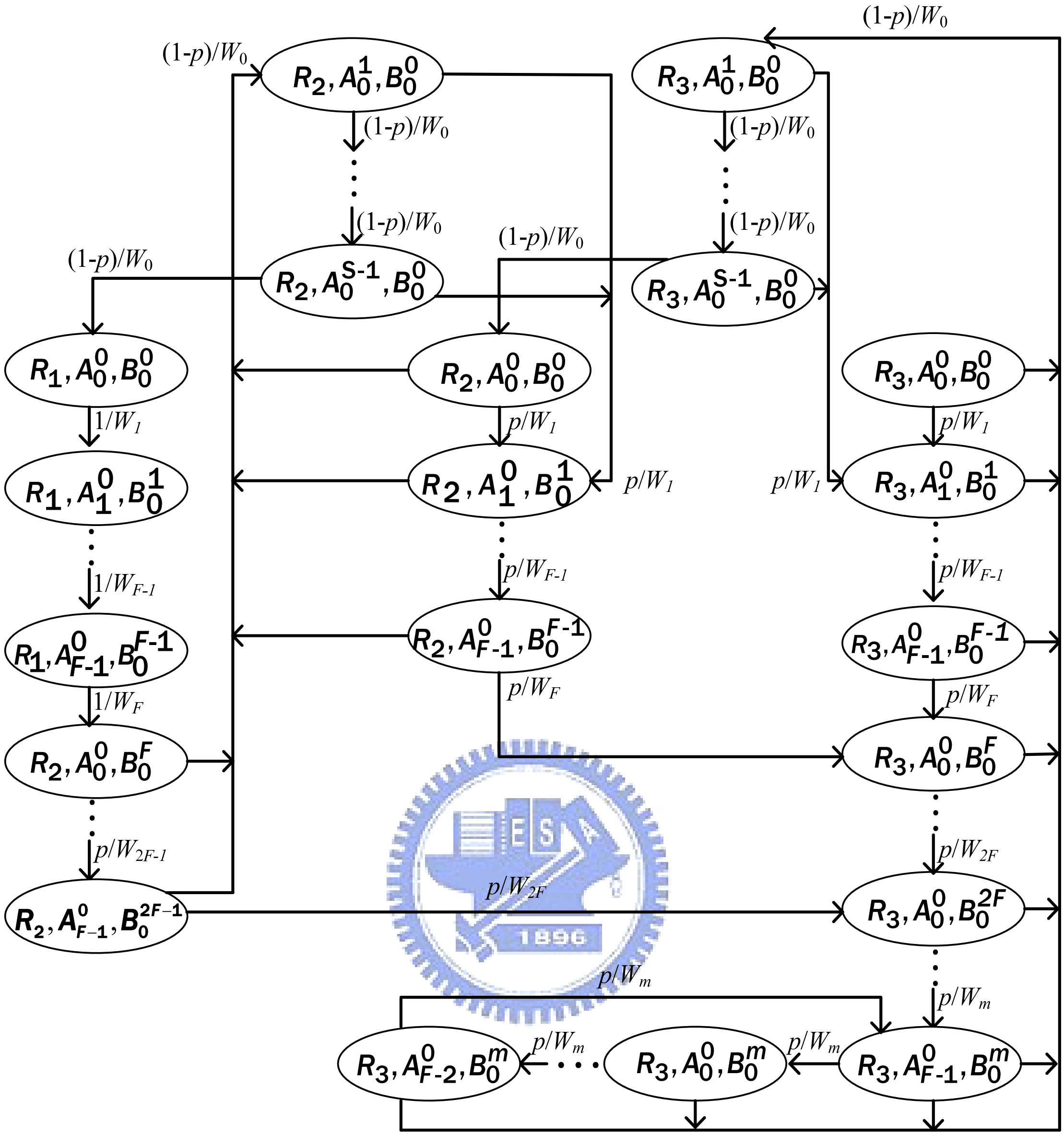


Figure 4.5: State transitions between transmission states in region2 of the AP.

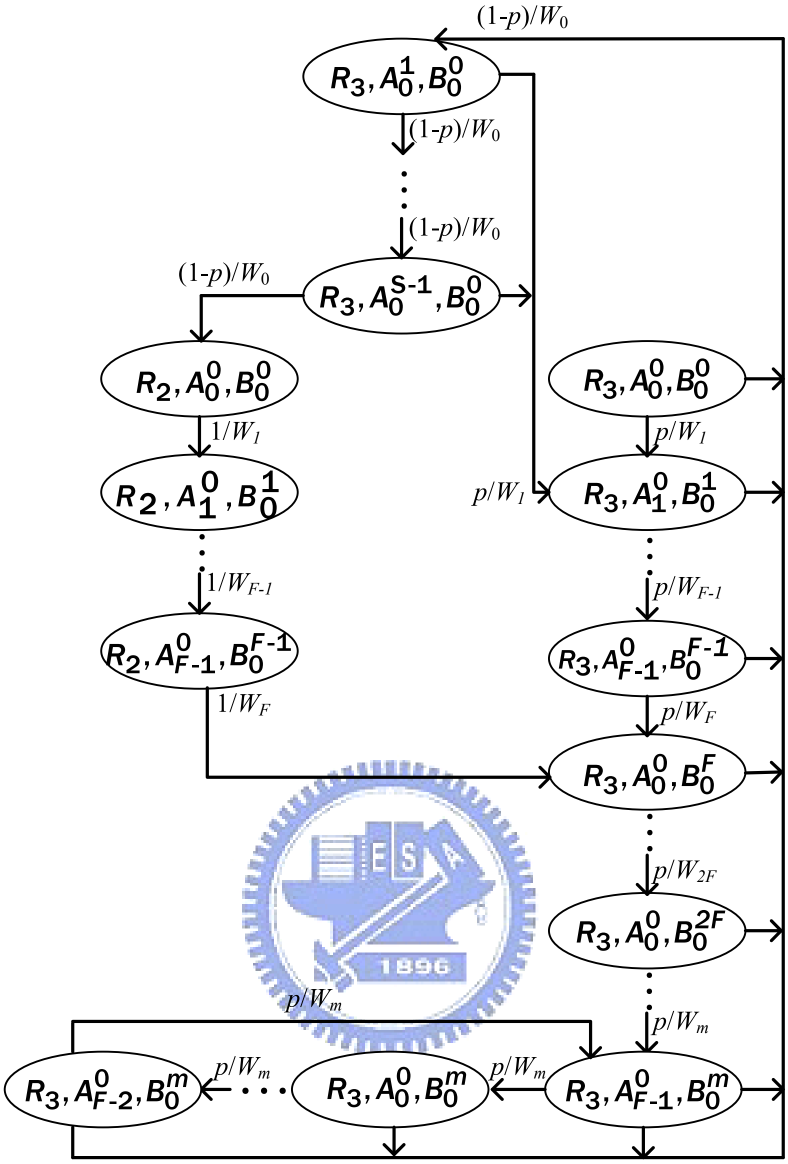


Figure 4.6: State transitions between transmission states in region3 of the AP.

mobile STAs having the multi-rate and ARF capability. In the analysis environment, a fixed number of mobile STAs are randomly distributed over the network area and each STA moves back and forth between the minimum distance 0 and maximum distance d_3 from the AP at the speed of v m/sec, as illustrated in Fig. 3.2. The STAs in the network will contend to send data packets to the Server through the AP using the DCF protocol. For ease of illustration, we assume that the mobile STAs and the AP only support 3 rates R_1, R_2, and R_3 with maximum transmission ranges d_1, d_2, and d_3, respectively. The network area therefore can be divided into 3 regions by assuming that the AP is located at the center of the network. When the distance d between a mobile STA and the AP falls in the range $0 \leqq d \leqq d_1$, $d_1 < d \leqq d_2$, or $d_2 < d \leqq d_3$, we say the STA is moving in region1, region2, or region3 of the AP, respectively. Fig. 3.3 shows an example of the state transitions between two successive backoff stages of the Rate-Adaptive Markov Chains. Figs. 3.4, 3.5, and 3.6 only show the state transitions between transmission states of the Chains when an STA is moving in region1, region2, and region3 of the AP, respectively. Each state in the Chains is represented by a 3-tuple of the form (R, A_f^s, B_k^i), where R is the rate used in transmissions, s/f is the current number of consecutive successes/losses, and i/k is the backoff stage number/backoff counter value. S/F is the maximum number of consecutive successes/losses before switching rates, and a rate change is performed when $s = S$ or $f = F$. The contention window size at the ith backoff stage is defined as $W_i = 2^i \times W_{min}$ when $0 \leqq i < m$ and $W_i = W_{max} = 2^m \times W_{min}$ when $i \geq m$, where m is the maximum backoff stage and W_{min} is the minimum window size. The backoff counter value k is uniformly distributed between 0 and $W_{i\text{-}1}$ at stage i and a packet can be transmitted when $k = 0$, called transmission state in the Markov Chains. The probability of collision p is independent of the transmission rate and the number of retransmissions of a packet; and it depends only on the number of mobile STAs contained in the network. From Fig. 3.3, we can see that if the current state of an STA is $(R, A_{f-1}^0, B_0^{i-1})$, then:

1. The STA will transit to $(R, A_f^0, B_k^i)/(R, A_0^1, B_k^0)$ with probability $\dfrac{p}{W_i}/\dfrac{(1-p)}{W_0}$ for a successful/failed transmission.
2. There is a probability of p_{tm} that the STA will freeze its backoff counter; This

can happen when the channel is sensed busy by the STA.

When an STA moves in the range between 0 and d_1 (region1), the state transitions of the STA can be described by Figs. 3.3 and 3.4. Figs. 3.3 and 3.5 together show the state transitions of a host when it moves in the range between d_1 and d_2 (region2) from the AP. Also, Figs. 3.3 and 3.6 together show the state transitions of an STA when it moves in the range between d_2 and d_3 (region3) from the AP.

Recall from (3.1), when mobile STAs are moving in region1 of the AP, all 3 rates may be used to send packets, and packet collision is the only source of transmission error. In addition to the packet collisions, out-of-transmission-range errors will also occur when the highest transmission rate, R_1, is used by STAs moving in region2. When STAs are moving in region3, rate R_1 will never be used by ARF, and using rate R_2 will always result in out-of-transmission-range errors. Therefore, the Chain in Fig. 3.5 is obtained from that in Fig. 3.4 by considering the fact that using rate R_1 will always fail, and setting the transmission error probability of using rate R_2 to 1 in Fig. 3.5 results in the Chain in Fig. 3.6.

4.2 Throughput Analysis

In the followings we divide the analysis into four steps. In the first three steps, we will show how to use the Rate-Adaptive Markov Chains to evaluate the saturation throughput of the network by assuming that all STAs are moving only in region1, region2, or region3 of the AP. Then the more general situation in which the STAs are moving in all of the 3 regions is considered.

4.2.1 Step 1: All Mobile STAs Moving only in Region1 of the AP

From state transitions in Figs. 3.3 and 3.4, we can obtain the following steady state probabilities b_{R,A_f^s,B_k^i} for a mobile host in the state (R, A_f^s, B_k^i):

$$b_{R_1,A_0^s,B_k^0} = \frac{1}{1-p_{tm}} \times \frac{W_0-k}{W_0} \times b_{R_1,A_0^s,B_0^0}, \quad 1 \le s \le S-1, 0 \le k \le W_0 - 1 \tag{3.2}$$

$$b_{R_1,A_f^0,B_k^i} = \frac{1}{1-p_{tm}} \times \frac{W_i-k}{W_i} \times b_{R_1,A_f^0,B_0^i}, \quad 0 \le i, f \le F-1, 0 \le k \le W_i - 1 \tag{3.3}$$

$$b_{R_2,A_0^s,B_k^0} = \frac{1}{1-p_{tm}} \times \frac{W_0-k}{W_0} \times b_{R_2,A_0^s,B_0^0}, \quad 1 \le s \le S-1, 0 \le k \le W_0 - 1 \tag{3.4}$$

$$b_{R_3,A_f^0,B_k^i} = \frac{1}{1-p_{tm}} \times \frac{W_i-k}{W_i} \times b_{R_3,A_f^0,B_0^i}, \quad 1 \le i \le m, 0 \le f \le F-1, 0 \le k \le W_i - 1 \tag{3.5}$$

$$b_{R_3,A_f^0,B_k^m} = \frac{1}{1-p_{tm}} \times \frac{W_m-k}{W_m} \times b_{R_3,A_f^0,B_0^m}, \quad 0 \le f \le F-2, 0 \le k \le W_m - 1 \tag{3.6}$$

$$b_{R_3,A_f^0,B_k^i} = \frac{1}{1-p_{tm}} \times \frac{W_i-k}{W_i} \times b_{R_3,A_f^0,B_0^i}, \quad 1 \le i \le m, 0 \le f \le F-1, 0 \le k \le W_i - 1 \tag{3.7}$$

$$b_{R_3,A_f^0,B_k^m} = \frac{1}{1-p_{tm}} \times \frac{W_m-k}{W_m} \times b_{R_3,A_f^0,B_0^m}, \quad 0 \le f \le F-2, 0 \le k \le W_m - 1 \tag{3.8}$$

Based on the Eqs. (3.2) to (3.8), we can express all state probabilities as functions of b_{R_1,A_1^0,B_0^1}. Then b_{R_1,A_1^0,B_0^1} can be expressed in terms of *S*, *F*, *m*, and *p* by using the following normalization condition:

$$1=\sum_{\substack{0\le i\le F-1\\0\le f\le F-1}}\sum_{k=0}^{W_i-1}b_{R_1,A_f^0,B_k^i}+\sum_{s=1}^{S-1}\sum_{k=0}^{W_0-1}b_{R_1,A_0^s,B_k^0}+\sum_{\substack{0\le i\le 2F-1\\0\le f\le F-1}}\sum_{k=0}^{W_i-1}b_{R_2,A_f^0,B_k^i}+\sum_{s=1}^{S-1}\sum_{k=0}^{W_0-1}b_{R_2,A_0^s,B_k^0}+$$

$$\sum_{\substack{0\le i\le m\\0\le f\le F-1}}\sum_{k=0}^{W_i-1}b_{R_3,A_f^0,B_k^i}+\sum_{s=1}^{S-1}\sum_{k=0}^{W_0-1}b_{R_3,A_0^s,B_k^0}+\sum_{f=0}^{F-2}\sum_{k=0}^{W_m-1}b_{R_3,A_f^0,B_k^m} \qquad (3.9)$$

The probability p_{tx} that a mobile host may initiate a transmission in a randomly chosen time slot is:

$$p_{tx}=\sum_{\substack{0\le i\le F-1\\0\le f\le F-1}}b_{R_1,A_f^0,B_0^i}+\sum_{s=1}^{S-1}b_{R_1,A_0^s,B_0^0}+\sum_{\substack{0\le i\le 2F-1\\0\le f\le F-1}}b_{R_2,A_f^0,B_0^i}+\sum_{s=1}^{S-1}b_{R_2,A_0^s,B_0^0}+$$

$$\sum_{\substack{0\le i\le m\\0\le f\le F-1}}b_{R_3,A_f^0,B_0^i}+\sum_{s=1}^{S-1}b_{R_3,A_0^s,B_0^0}+\sum_{f=0}^{F-2}b_{R_3,A_f^0,B_0^m} \qquad (3.10)$$

Such a transmission will occur whenever the mobile host enters any one of the transmission states. From [2], the probabilities of packet collision[7] p and of busy channel[8] p_{tm} are:

$$p=1-(1-p_{tx})^{n-1} \qquad (3.11)$$

and

$$p_{tm}=1-(1-p_{tx})^{n}, \qquad (3.12)$$

---

[7] A collision occurs when one mobile host and one or more of the other hosts in the network transmit on the channel at the same time.

[8] A channel is said to be busy when there is at least one packet transmitted on the channel in a randomly chosen time slot, which in 802.11 has an interval of 20 μs.

where n is the number of mobile hosts in the network. If Packet Error Rate (PER) needs to be considered, the p in Eq. (3.11) will become

$$p^R = 1-(1-p_{tx})^{n-1} \times (1-e^R), \qquad (3.13)$$

where p^R is the probability of transmission error when rate R is used and e^R is the PER for rate R. For example, the e^R for the 4 rates supported by 802.11b networks can be found in [23].

Now we have a non-linear system of 4 equations, Eqs. (3.9) ~ (3.12), and 4 unknowns, b_{R_1,A_1^0,B_0^1}, p_{tx}, p, and p_{tm}, which can be solved by using numerical techniques for any given set of values of S, F, m, and n.

Recall that a mobile host in region1 may use all 3 supported rates to communicate with the AP, we denote by $p_{tx}^R = \frac{\sum \text{prob. of transmission using } R}{p_{tx}}$ the conditional probability that the transmission rate is R given that the host initiates a transmission on the channel. Therefore, we have

$$\begin{cases} p_{tx}^{R_1} = \dfrac{\sum \text{Prob. of Trans. using } R_1}{p_{tx}} = \dfrac{\sum_{0\le f\le F-1}^{0\le i\le F-1} b_{R_1,A_f^0,B_0^i} + \sum_{s=1}^{S-1} b_{R_1,A_0^s,B_0^0}}{p_{tx}} \\ p_{tx}^{R_2} = \dfrac{\sum \text{Prob. of Trans. using } R_2}{p_{tx}} = \dfrac{\sum_{0\le f\le F-1}^{0\le i\le 2F-1} b_{R_2,A_f^0,B_0^i} + \sum_{s=1}^{S-1} b_{R_2,A_0^s,B_0^0}}{p_{tx}} \\ p_{tx}^{R_3} = \dfrac{\sum \text{Prob. of Trans. using } R_3}{p_{tx}} = \dfrac{\sum_{0\le f\le F-1}^{0\le i\le m} b_{R_3,A_f^0,B_0^i} + \sum_{s=1}^{S-1} b_{R_3,A_0^s,B_0^0} + \sum_{f=0}^{F-2} b_{R_3,A_f^0,B_0^m}}{p_{tx}} \end{cases} \qquad (3.14)$$

In our analysis, we do not consider using the RTS/CTS technique. We evaluate the throughput at the application layer. Let T_{Succ}^R be the time needed for a successful transmission using rate R. In the followings, all transmission rates are in units of Mbps, frame sizes are in units of bits, and time is expressed in μs. Then,

$$\begin{cases} T_{Succ}^{R_1} = (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_{ACK}}) + t_{DIFS} \\ T_{Succ}^{R_2} = (t_{PLCP} + \frac{L_{MPDU}}{R_2}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_{ACK}}) + t_{DIFS} \\ T_{Succ}^{R_3} = (t_{PLCP} + \frac{L_{MPDU}}{R_3}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_{ACK}}) + t_{DIFS} \end{cases} \tag{3.15}$$

where L_{MPDU}/L_{ACK} is the length of the MAC Protocol Data Unit/ACK frame, R_{ACK} is the rate used to transmit ACK frames, $t_{ACK} = t_{PLCP} + L_{ACK}/R_{ACK}$, is the time needed to send ACK frames, and t_{SIFS}, t_{DIFS}, and t_{PLCP} are the time periods of Short Interframe Space, DCF Interframe Space, and the Physical Layer overhead, respectively. Similar to [1], $p_{tr} = 1 - (1 - p_{tx})^n$ is the probability that at least one transmission occurs on the channel in a randomly chosen time slot. The probability p_{Succ}^{R} that a transmission using rate R is successful is given by the probability that exactly one transmission occurs, under the condition that at least one host transmits on the channel:

$$\begin{cases} p_{Succ}^{R_1} = \frac{n \times (p_{tr} \times p_{tr}^{R_1}) \times (1 - p_{tr})^{n-1}}{p_{tr}} \\ p_{Succ}^{R_2} = \frac{n \times (p_{tr} \times p_{tr}^{R_2}) \times (1 - p_{tr})^{n-1}}{p_{tr}} \\ p_{Succ}^{R_3} = \frac{n \times (p_{tr} \times p_{tr}^{R_3}) \times (1 - p_{tr})^{n-1}}{p_{tr}} \\ \Rightarrow p_1^{Succ} = p_{Succ}^{R_1} + p_{Succ}^{R_2} + p_{Succ}^{R_3} \end{cases} \tag{3.16}$$

In Eq. (3.16), p_1^{Succ} is the probability of successful transmission using rate R_1, R_2, or R_3 in region1 of the AP, given at least one transmission taking place on the channel. From Eqs. (3.15) and (3.16), T_1^{Succ} is the average time needed for a successful transmission in region1:

$$T_1^{Succ} = p_{Succ}^{R_1} \times T_{Succ}^{R_1} + p_{Succ}^{R_2} \times T_{Succ}^{R_2} + p_{Succ}^{R_3} \times T_{Succ}^{R_3} \tag{3.17}$$

Table 4.1: The parameters used in simulations and analytical model.

Parameter	Value
Transmit Power	15 dBm
$R_1/R_2/R_3/R_{ACK}$	11.0/5.5/1.0/1.0 Mbps
$d_{min}/d_1/d_2/d_3 = d_{max}$	0/399/531/796 meters
Receive Threshold of $R_1/R_2/R_3$	-82/-87/-94 dBm
Propagation Model	Two Ray Ground
Link Propagation Delay	0
Packet Error Rate e^{R1} , e^{R2} , and e^{R3}	0
σ $/t_{DIFS}/t_{SIFS}/t_{PLCP}$	20/50/10/192 μs
W_{min}/m	31/5
$L_{App}/L_{MPDU}/L_{ACK}$	11712/12160/112 bits
Simulation Time	10000 secs

Let p_e^R be the probability that a collision occurs and the rate used by the slowest colliding host is R, conditioned on the fact that at least one transmission occurs on the channel. Therefore, we have

$$\begin{cases} T_e^{R_1} = (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{DIFS} + T_o \\ T_e^{R_2} = (t_{PLCP} + \frac{L_{MPDU}}{R_2}) + t_{DIFS} + To \\ T_e^{R_3} = (t_{PLCP} + \frac{L_{MPDU}}{R_3}) + t_{DIFS} + To \end{cases} \quad (3.19)$$

The $T_o = t_{SIFS} + (t_{PLCP} + L_{ACK}/R_{ACK})$ in Eq. (3.19) is the time that a colliding host has to wait before sensing the channel again. From Eqs. (3.18) and (3.19), we can obtain the average time spent in a failed transmission in region1 as follows:

$$T_1^e = p_e^{R_1} \times T_e^{R_1} + p_e^{R_2} \times T_e^{R_2} + p_e^{R_3} \times T_e^{R_3} \quad (3.20)$$

The normalized network throughput Th_1, expressed in Mbps and defined as the fraction of time that the channel is used to successfully transmit user bits when hosts are only moving in region1 of the AP, is:

$$Th_1 = \frac{E[\text{user bits transmitted in a time slot}]}{E[\text{length of a time slot}]} = \frac{p_{tr} \times p_1^{Succ} \times L_{App}}{(1 - p_{tr}) \times \sigma + p_{tr} \times T_1^{Succ} + p_{tr} \times T_1^{e}}, \qquad (3.21)$$

where L_{App} is the packet size at the application layer and σ is the idle slot time.

4.2.2 Steps 2 and 3: All Mobile STAs Moving only in Region2 or Region3 of the AP

Since the Markov Chains for STAs moving in region2 or region3 of the AP are obtained from those of region1, the saturation throughput Th_2/Th_3 when all STAs are only moving in region2/region3 of the AP can be easily obtained by following the same procedures as those in Sec. 3.2.1. Thus the expressions for Th_2 and Th_3 have the same form as that in Eq. (3.21).

4.2.3 Step 4: The General Situation

Now we consider the general situation where the STAs are moving between the minimum distance 0 and the maximum distance d_3 from the AP. That is, the STAs in the network move in all 3 regions of the AP. In this case, the saturation throughput of the network Th can be evaluated by noting that the transmission distance between an STA and the AP can be considered to be uniformly distributed in the range $[0, d_3]$. Therefore

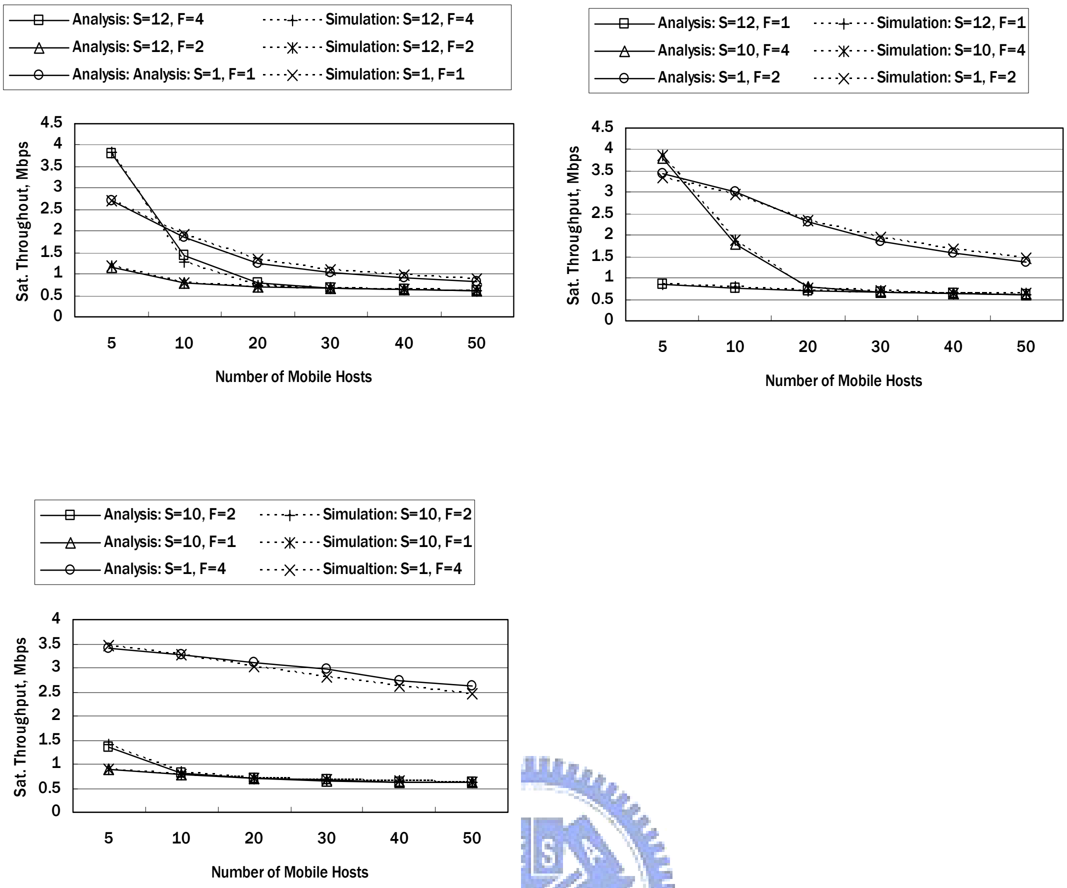


Figure 4.7: Saturation throughput: simulation versus analysis.

$$Th = \frac{d_1}{d_3} \times Th_1 + \frac{d_2 - d_1}{d_3} \times Th_2 + \frac{d_3 - d_2}{d_3} \times Th_3 \qquad (3.22)$$

4.2.4 Validation of the Analytical Model

The proposed model is verified by a simulation program, written in the C++ programming language that closely follows the 802.11 DCF and ARF protocols. The values of the parameters used to obtain analytical and simulation results are summarized in Table 3.1, which are also used in [7, 24]. The network environment in Fig. 3.2 is considered in simulations. In simulations, the hosts in the network are

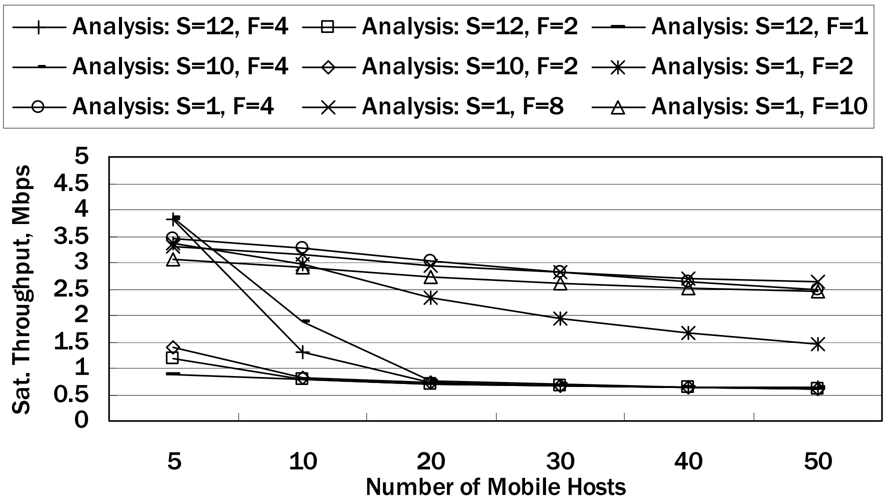
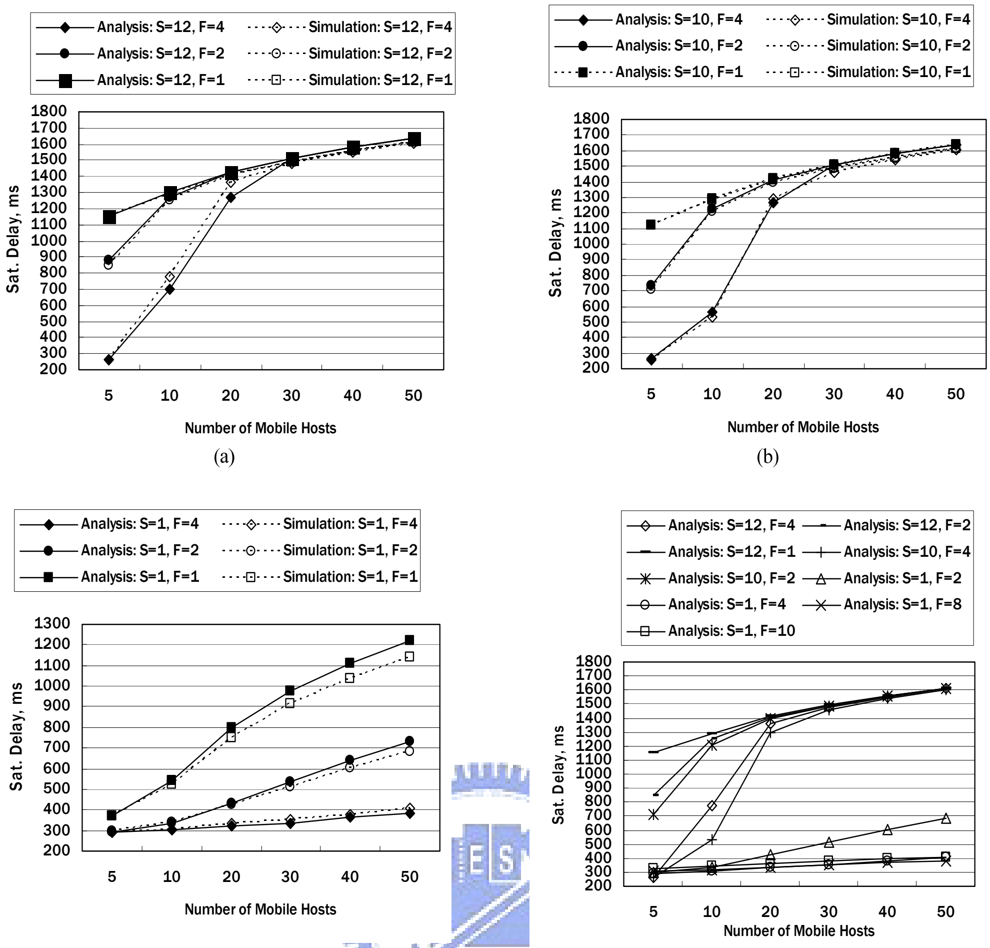


Figure 4.8: The saturation throughput for STAs moving in all 3 regions of the AP.

considered to move back and forth between the minimum distance of d_{min} = 0 and maximum distance of d_{max} = 796 meters from the AP with the speed of v = 1 meters/sec. The saturation throughput from both the analytical model and the simulation runs for different numbers of mobile hosts and various values of the ARF parameters S and F is shown in Fig. 3.7. From this figure, we can see that the analytical results match very well with the simulation results, so the correctness our model is justified. To compare the throughput, the same results are also shown in Fig. 3.8. From these results, we can see that in order for a network to have better throughput performance, a smaller S and a larger F than those used in [10][9] should be chosen.

Since the packet error rate is set to be 0 in our analysis, a transmission will fail only when either collision occurs or the maximum transmission range at the current rate is exceeded. According to the observations from our analysis, the main reason for

[9] Recall that the ARF parameters S and F used by WaveLAN-II devices are 10 and 2, respectively.



(c) (d)

Figure 4.9: The saturation delay.

mobile hosts moving within the same region of the AP to experience consecutive transmission failures is because of the first one, not the second one stated above. Therefore, setting the parameter F to have a higher value than that used in [10] to avoid drastic reductions in data rates has positive effect on throughput performance. On the other hand, a too high value of F will have negative effect on throughput performance when a host is crossing the border from a region nearer the AP to the region further from the AP. When a mobile host is crossing a region border toward the AP, setting the parameter S to a smaller value so that the host can use the most appropriate transmission rate earlier will also benefit the network throughput.

4.3 The Delay Analysis

Based on the proposed model, in this section we will conduct the delay analysis. The analysis is similar to that for the throughput analysis. As in [2], packet delay is defined as the time interval between the generation of a packet and the success of its reception. Let D_i be the random variable denoting the packet delay and $E[D_i]$ the mean of the delay for STAs moving in the ith region of the AP, where i = 1, 2, or 3. Then

$$E[D_i] = E[C_i] \times (E[B_i] + T_i^e) + (E[B_i] + T_i^{Succ}) \quad (3.23)$$

In Eq. (3.23), $E[C_i] = \frac{1}{p_i^{Succ}} - 1$ is the average number of failures of a packet until its success of reception, and p_i^{Succ} is the probability of successful transmission for hosts moving in the ith region of the AP. $E[B_i]$ is the average time of the backoff delay, and T_i^{Succ} / T_i^e is the time needed for a successful/failed transmission. The expressions for $p_1^{Succ}, T_1^{Succ}, T_1^e$ are already given in Eqs. (3.16), (3.17) and (3.20), respectively, so we omit the details. Those probabilities/variables for i = 2 and 3 are as follows:

$$\begin{cases} p_1^{Succ} = p_{Succ}^{R1} + p_{Succ}^{R2} + p_{Succ}^{R3} \\ T_1^{Succ} = p_{Succ}^{R1} \times T_{Succ}^{R1} + p_{Succ}^{R2} \times T_{Succ}^{R2} + p_{Succ}^{R3} \times T_{Succ}^{R3} \\ T_1^e = p_e^{R1} \times T_e^{R1} + p_e^{R2} \times T_e^{R2} + p_e^{R3} \times T_e^{R3} \\ p_2^{Succ} = p_{Succ}^{R2} + p_{Succ}^{R3} \\ T_2^{Succ} = p_{Succ}^{R2} \times T_{Succ}^{R2} + p_{Succ}^{R3} \times T_{Succ}^{R3} \\ T_2^e = p_e^{R1} \times T_e^{R1} + p_e^{R2} \times T_e^{R2} + p_e^{R3} \times T_e^{R3} \\ p_3^{Succ} = p_{Succ}^{R3} \\ T_3^{Succ} = p_{Succ}^{R3} \times T_{Succ}^{R3} \\ T_3^e = p_e^{R2} \times T_e^{R2} + p_e^{R3} \times T_e^{R3} \end{cases} \quad (3.24)$$

Let X_i be the random variable representing the time needed for an STA in state

b_{R,A_f^s,B_k^x} to reach the transmission state b_{R,A_f^s,B_0^x}, excluding the time when the backoff counter is frozen. Then, the average of this time interval, in time slots, is

$$\begin{aligned} E[X_i] = & \sum_{\substack{0 \le i \le F-1 \\ 0 \le f \le F-1}} \sum_{k=1}^{W_i-1} k \times b_{R_1,A_f^0,B_k^i} + \sum_{s=1}^{S-1} \sum_{k=1}^{W_0-1} k \times b_{R_1,A_0^s,B_k^0} + \\ & \sum_{\substack{0 \le i \le 2F-1 \\ 0 \le f \le F-1}} \sum_{k=1}^{W_i-1} k \times b_{R_2,A_f^0,B_k^i} + \sum_{s=1}^{S-1} \sum_{k=1}^{W_0-1} k \times b_{R_2,A_0^s,B_k^0} + \\ & \sum_{\substack{0 \le i \le m \\ 0 \le f \le F-1}} \sum_{k=1}^{W_i-1} k \times b_{R_3,A_f^0,B_k^i} + \sum_{s=1}^{S-1} \sum_{k=1}^{W_0-1} k \times b_{R_3,A_0^s,B_k^0} + \sum_{f=0}^{F-2} \sum_{k=1}^{W_m-1} k \times b_{R_3,A_f^0,B_k^m} \end{aligned} \tag{3.25}$$

Denoting $E[Z_i]$ as the average number of times that an STA in the ith region of the AP senses a busy channel before reaching the transmission state, then we have

$$E[Z_i] = \frac{E[X_i]}{\max(E[Y_i],1)} - 1, \tag{3.26}$$

where $E[Yi] = (1/p_{tm}) - 1$ is the average number of consecutive idle time slots before a transmission occurred on the channel. Therefore, $E[B_i] = E[X_i] \times \sigma + E[N_i]$, where $E[N_i] = E[Z_i] \times (p_i^{Succ} \times T_i^{Succ} + (1 - p_i^{Succ}) \times T_i^e)$ is the average time, in μs, that the backoff counter of an STA is stopped and σ is the time period, in μs, of an idle time slot.

Finally, the average packet delay, in μ s, for STAs moving in all 3 regions of the AP can be calculated as follows:

$$E[D] = \frac{d_1}{d_3} \times E[D_1] + \frac{d_2 - d_1}{d_3} \times E[D_2] + \frac{d_3 - d_2}{d_3} \times E[D_3] \tag{3.27}$$

The analytical and simulation results are shown in Fig. 3.9(a) ~ (c) for various ARF parameter values and numbers of mobile STAs. From Fig. 3.9(d), we can see that in order for a packet to experience lower delay than the standard ARF, a smaller *S* and a larger *F* need to be used, which are consistent with the arguments made in throughput analysis.

4.4 Concluding Remarks and Future Works

In this chapter, we have presented an analytical model to evaluate the saturation throughput and delay performance of the 802.11 DCF in an environment where mobile STAs have multi-rate support. We assume that the ARF protocol is adopted by wireless interfaces for choosing transmission rates. Although some previous works have studied the performance of a WLAN with STAs having the ARF capability, they all are done by simulations. As far as we know, we are the first to study the performance of a multi-rate WLAN using an analytical model. The proposed model has been verified by extensive simulations. From simulation and analytical results, we conclude that in a slowly changing channel, a smaller S and a larger F for the ARF protocol than those used by WaveLAN-II devices need to be set, so that better network performance can be achieved. Although an ideal wireless channel is considered in our analysis, the proposed model can also be used in a noisy channel condition by taking into account of packet error rate to more closely reflect the real situation.

The following are some of the problems that may be considered as the future works on the Rate Adaptive Markov Chains:

1. We hope to further extend the Markov model to take into account the bit errors incurred in the packet transmissions.
2. How the Markov model can be used to interact with the upper layer protocols, such as the TCP/IP?

Chapter 5

Route Selections in Multi-Rate Multi-Hop Ad Hoc Networks

5.1 Routing in Multi-Rate Multi-Hop Ad Hoc Networks

Routing is one of the most intensively addressed issues in multi-hop ad hoc networks. As stated in [25], the previous routing algorithms [26, 27, 28] have focused on discovering and maintaining routes that enable connectivity between STAs in the network and have the minimum number of hops. Since the wireless STAs are normally powered by batteries, such a routing policy is good for overall energy efficiency because energy needed to transmit a packet is correlated to the path length in a single rate ad hoc network. However, the shortest path may not be the most throughput efficient among all possible paths between a pair of source and destination STAs in an environment in which STAs may use different transmission rates. Therefore, we argue that path throughput is a better metric than the hop count for route selection in multi-rate ad hoc networks.

5.2 Throughput of a Static Route

In this section, we will show how to estimate the throughput of a given n-hop route $R = [r_1, r_2, \bullet\ \bullet\ \bullet, r_n]$, where r_i, $1 \leqq i \leqq n$, is the rate used on the ith link of R.

Table 5.1: Summary of simulation parameters.

Parameter	Value
Frequency	2.4 GHz
Transmit Power	15 dBm
11.0 Mbps Receive Threshold	-82 dBm
5.5 Mbps Receive Threshold	-87 dBm
2.0 Mbps Receive Threshold	-91 dBm
1.0 Mbps Receive Threshold	-94 dBm
Carrier Sense Threshold	-108 dBm
Capture Threshold	10 dB
Propagation Model	Two Ray Ground
System Loss	0 dB
11.0 Mbps Max. Transmission Range	399 m
5.5 Mbps Max. Transmission Range	531 m
2.0 Mbps Max. Transmission Range	669 m
1.0 Mbps Max. Transmission Range	796 m
Carrier Sense Range	1783 m
σ /t_{DIFS}/t_{SIFS}/t_{PLCP}	20/50/10/192 μs
RTS/CTS/ACK	20/14/14 bytes
W_0/W_{max}	31/1023

An ideal channel condition is assumed in the estimation such that a transmission fails only when collisions occur.

The STAs on R are numbered from 1 to n + 1 such that STA 1 is the traffic source and STA n + 1 the sink of the path. Therefore r_i is the rate used by STA i to communicate with STA $i + 1$. Except the sink STA, we can assign each STA i on R a carrier sense group G_i, which contains all STAs that will sense the signal from STA i when it is transmitting. Intuitively, STAs in the same group will not transmit at the same time, but STAs from different groups are allowed to transmit simultaneously (the CSMA/CA of 802.11). We then model the cycle time T_i of STA i as follows, which means how much time in average it requires for STA i to successfully transmit one packet by taking into consideration of all factors, such as collisions, contention time, and transmission time.

$$T_i = \sum_{x \in G_i} \sum_{y=0}^{\infty} [p^y \times (1-p) \times (\sum_{z=0}^{y-1} t_{DIFS} + \frac{W_z}{2} \times \sigma + T_{col}) + (t_{DIFS} + \frac{W_y}{2} \times \sigma + T_{Succ})], \quad (4.1)$$

where

$$T_{col} = t_{PLCP} + \frac{RTS}{r_b} + t_{CTSTimeout}, \quad (4.2)$$

$$T_{Succ} = (t_{PLCP} + \frac{RTS}{r_b}) + t_{SIFS} + (t_{PLCP} + \frac{CTS}{r_b}) + t_{SIFS} + (t_{PLCP} + \frac{L_{pkt}}{r}) + t_{SIFS} + (t_{PLCP} + \frac{ACK}{r}), \quad (4.3)$$

and

$$T_{CTSTimeout} = (t_{PLCP} + \frac{CTS}{r_b}) + t_{SIFS} \quad (4.4)$$

In Eq. (4.1), we consider all STAs in the carrier sense group of STA i. Under an ideally fair situation, each STA in G_i may have a chance to transmit one packet in time interval T_i in a round-robin manner. The first summation in T_i is to reflect such a requirement. The second summation in T_i is to take into account the number of collisions an STA may experience before it successfully transmits a packet. The probability that an STA experiences y collisions before success is $p^y = (1- p)$, where p is the packet collision probability and is approximated in [1] as $p = 1 - (1 - \tau)^{|Gi|-1}$, and the probability of packet transmission τ in a time slot is:

$$\tau = \frac{2(1-2p)}{(1-2p)(W_0+1)+pW_0(1-(2p)^s)}, \qquad (4.5)$$

where W_0 is the minimum contention window size. Note that s is the number of retries before reaching the maximum contention window W_{max}; that is, $2^s = (W_{max}+1)/(W_0+1)$.

Inside the third summation of T_i is the transmission cost of the zth fail, which includes a t_{DIFS} interval (in μs), an average backoff time of W_z= 2 times the length of a time slot σ (in μs), and a collision cost of T_{col}. With the exponential backoff rule, W_z is defined as $\min(2^z \times (W_0 + 1) - 1, W_{max})$.

The last term in the second summation of Eq. (4.1) is the cost when a packet is transmitted successfully, which includes a t_{DIFS} interval, a backoff time interval, and a success cost T_{succ}. Eqs. (4.2) and (4.3) model the success and collision costs, respectively. The t_{PLCP} is the PHY overhead (in μs) for packet preamble and header. *RTS*, *CTS*, and *ACK* are the lengths of the Ready-to-Send, Clear-to-Send, and Acknowledgement control frames, respectively (in bits). L_{pkt} is the average size of a MAC Protocol Data Unit (MPDU) frame (in bits). The t_{SIFS} is the Short Inter Frame Space defined in IEEE 802.11 (in μs). r_b is the basic rate (in Mbps), which is always used in transmitting RTS and CTS control frames, and r is the rate used by STA x to transmit MAC and ACK frames. $T_{CTSTimeout}$ is the cost of the CTS timeout, which includes a CTS transmission time and a t_{SIFS} in [29].

Since STA i can transmit one MAC frame in average in each T_i period, the throughput of the link from STA i to STA i+1 can be modeled by $(L_{pkt}-O_{pkt})/T_i$ Mbps, where O_{pkt} is the packet overheads from the MAC layer up to the application layer. Therefore, the throughput of the path R can be modeled by

Table 5.2: Path throughput from simulations and analysis.

Path	Link States	Path Throughput	
		Simulation (ns2)	Analysis
1	[(11/200),(5.5/300),(2/400),(1/500)]	0.429	0.407
2	[(5.5/500),(5.5/500),(5.5/300),(11/300),(11/300),(11/300),(11/300),(11/300)]	0.469	0.411
3	[(11/300),(11/300),(11/300),(11/300),(5.5/500),(5.5/500),(5.5/500),(5.5/500)]	0.386	0.4
4	[(5.5/300),(5.5/300),(5.5/300),(5.5/400),(2/400),(2/500),(2/500),(2/500)]	0.23	0.238
5	[(5.5/400),(5.5/400),(5.5/400),(5.5/350),(11/350),(11/350),(11/350),(11/350),(2/500),(2/500),(2/500),(2/500)]	0.243	0.235
6	[(11/300),(11/300),(5.5/400),(5.5/400),(2/500),(2/350),(11/350),(11/350),(5.5/400),(5.5/400),(2/500),(2/500)]	0.245	0.225

$$Th(R) = L_{pkt} \times min\{ \frac{1}{T_1}, \frac{1}{T_2}, \cdots, \frac{1}{T_n} \} \quad (4.6)$$

5.3 Validation of the Proposed Model

We have developed a simulator based on C++ and the *ns*-2 [29] is used to verify the method derived in Sec. 4.2. We consider the 802.11b interfaces. The parameters used in our simulations follow those in [24, 7] and are summarized in Table 4.1. The basic rate r_b is always set to 1.0 Mbps to transmit RTS, CTS, and ACK control packets. Since we do not simulate the physical layer, the propagation delay is ignored. To verify the proposed method, we simulate a static route on which a UDP connection is established. A CBR (Constant Bit Rate) traffic is injected at the source STA with the packet size set to be 1464 bytes. The throughputs (in Mbps) for a number of randomly generated paths are listed in Table 4.2. Each link in the path is described by (r/l), where r is the transmission rate (in Mbps) and l is the distance (in meters) between the two endpoints of a link. From this table, we can see that the proposed method does give a very high degree of accuracy in evaluating path throughput.

5.4 Expected Throughput of a Dynamic Route

In order to evaluate the expected throughput of a dynamic route, we need a mobility model for the users in a wireless network. Existing mobility models for ad hoc networks include Random Waypoint [26] and Random Walk [30]. By virtue of their simplicity, these random models allow researchers to simplify the comparison of results generated by different protocols. In random waypoint, for instance, users simply move among randomly chosen locations with a parameterized speed and wait-time at each location. The hope is that a simple model captures enough of the key characteristics of human mobility to make protocol evaluations meaningful. However, such random models are not representative of real-world mobility scenarios. For instance, in a beach scenario, mobile users don't move in a random manner. Beach users are unevenly distributed over the landscape. Some of them may be stationary and others move at different characteristic speeds: walkers, joggers, bikers, sun-bathers and volleyball-players. The course that mobile users take is not random. Rather, some of their movements tend to be toward certain attraction points such as volleyball playing spots, washrooms and snack bars; while others move in a predefined path through the landscape.

Therefore, the next step of our work in this subject is to develop a practical user mobility model such that the expected throughput of a dynamic route can be evaluated as in [37], and then finally a routing protocol that selects the most throughput efficient path from all possible paths can be designed.

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