Performance Analysis of IEEE 802.11 DCF in a Multi-Rate WLAN

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Abstract

The IEEE 802.11 family of specifications is by far the most prominent and successful technique for accessing WLANs. Because the channel used by wireless devices is a time-varying broadcast medium, these devices need to have multi-rate and rate-adaptive capability to adapt to the changing channel so that better performance can be achieved. In this paper, we proposed an analytical model, which we call Rate-Adaptive Markov Chains, to study the saturation throughput and delay performance of a 802.11 WLAN in which the mobile hosts have multi-rate support, will use the ARF protocol to adapt rates for different channel qualities, and follow the DCF protocol to contend for data transmissions in a slowly-varying channel. Simulation results are also provided to verify the correctness of the model.

1 Introduction

In recent years, the family of IEEE 802.11 protocols has become the most popular access method for Wireless LANs (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. 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]. 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 within the access point (AP) 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. Since DCF is implemented in most of 802.11-compliant products, we will in this paper focus our attentions on this scheme.

Because of the signal fading, transmission interference, and user mobility, wireless channels have time varying characteristics. Therefore different mobile hosts may perceive different channel qualities at the same time. In order to obtain optimum good throughput, the hosts in the network need to use different transmission rates for different channel qualities [5]. Currently most protocols, including IEEE 802.11b, 802.11a, 802.11g, and HiperLAN-II, have this multi-rate support. In [6], the authors analyzed the DCF performance for finite load hosts in a multi-rate environment in which different hosts may use different transmission rates, but each host still only uses the same rate for all of its transmissions.

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. The algorithm for performing rate switching is unspecified in 802.11, and few rate adaptation techniques have been designed for WLANs in the literature. Among those that are available, the following are the most important. In [9], 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 modified ARF protocols are therefore proposed [11, 12]. RBAR [10] is the only other published rate adaptation algorithm for 802.11. In RBAR, a pair of RTS/CTS frames is exchanged between the sender and 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 CTS frame. The results from [10] show that RBAR does have a more efficient rate adaptation capability than that of the ARF. But the problems with RBAR are (1) a RTS/CTS frame exchange is always needed even no hidden hosts are present; and (2) the formats of the RTS/CTS frames need to be modified, so it can not be used in existing networks. Therefore, in the rest of the paper, we will focus our attentions on the ARF protocol.

In this paper, 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 hosts have multi-rate support and will use ARF to adapt rates for different channel qualities.

In our performance analysis, the following assumptions are made: (1) Each host always has a packet ready for transmission so that the saturation throughput performance of the network can be evaluated; (2) The mobile hosts support $\alpha$ rates, $R_1 > R_2 > \cdots > R_\alpha$, and the maximum transmission range of $R_i$ is $d_i$, $i=1, 2, \cdots, \alpha$. Since there exists a tradeoff between rate and range, the following relations hold for these ranges: $0 < d_1 < d_2 < \cdots < d_\alpha$; (3) The hosts in the network follow the ARF protocol to perform rate switching; and (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 the distance $d$ between them are:

$$
\begin{align*}
R &= R_1, R_2, \cdots, R_\alpha & \text{if } 0 \leq d \leq d_1 \\
R &= R_{i-1}, R_i, \cdots, R_\alpha & \text{if } d_{i-1} < d \leq d_i \text{ and } 2 \leq i \leq \alpha
\end{align*}
$$

(1)

The first relation in (1) indicates that a sender will use all supported rates
to send packets when \( d \) is in the range between 0 and \( d_1 \); and although rate \( R_{i-1} \) will be used for transmissions when \( d \) falls in the range \( d_{i-1} < d \leq d_i \), those transmissions will always fail due to out of transmission range.

Because of user mobility, the distance between a sender and its receiver will change with time. 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 this paper.

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. 1, in which \( s/f \) is the current number of successes/losses and \( S/F \) is the maximum number of consecutive successes/losses before changing rates. To the authors’ best knowledge, we are the first to propose an analytical model that combines both 802.11 DCF and ARF.

The rest of the paper is organized as follows. Section 2 presents the Rate-Adaptive Markov Chains and shows how they are used in saturation throughput analysis. In section 3, the accuracy of the model is validated by simulations. The delay performance is analyzed in section 4. Concluding remarks are given in Section 5.

## 2 Throughput Analysis

We will in this section present the Rate-Adaptive Markov Chains and show how to use them to evaluate the saturation throughput performance of the DCF for a given number of mobile hosts having the multi-rate and ARF capability. In the analysis environment, a fixed number of mobile hosts are randomly distributed over the network area and each host moves back and forth between the minimum distance \( d_{\text{min}} \) and maximum distance \( d_{\text{max}} \) from
Figure 3: An example of the state transitions between two successive backoff stages of the Rate-Adaptive Markov Chains.

Figure 4: The state transitions between transmission states when a mobile host is moving in region1 of the AP.
Figure 5: The state transitions between transmission states when a mobile host is moving in region 2 of the AP.

Figure 6: The state transitions between transmission states when a mobile host is moving in region 3 of the AP.
the AP with the speed of $v$ m/sec, as illustrated in Fig. 2. The hosts 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 the mobile hosts 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 host and the AP falls in the range $0 \leq d \leq d_1$, $d_1 < d \leq d_2$, or $d_2 < d \leq d_3$, we say the host is moving in region1, region2, or region3 of the AP, respectively. Fig. 3 shows an example of the state transitions between two successive backoff stages of the Rate-Adaptive Markov Chains. Figs. 4, 5, and 6 only show the state transitions between transmission states of the Chains when a host 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 $(R, A_s^f, B_i^k)$, 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 $i$th backoff stage is defined as $W_i = 2^i \times W_{\min}$ when $0 \leq i < m$ 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 $W_i - 1$ 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 hosts contained in the network. From Fig. 3, we can see that if the current state of a host is $(R, A_s^f, B_i^k)$, then (1) The host will transit to $(R, A_s^0, B_i^k)$ with probability $\frac{p}{W_i}$; and (2) The probability of $p_{tm}$ that the host will freeze its backoff counter. This can happen when the channel is sensed busy by the host. When a host moves in the range between $d_{\min} = 0$ and $d_{\max} = d_1$ (region1), the state transitions of the host can be described by Figs. 3 and 4. Figs. 3 and 5 together show the state transitions of a host when it moves in the range between $d_{\min} = d_1$ and $d_{\max} = d_2$ (region2) from the AP. Also, Figs. 3 and 6 together show the state transitions of a host when it moves in the range between $d_{\min} = d_2$ and $d_{\max} = d_3$ (region3) from the AP. Recall from (1), when mobile hosts 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 hosts moving in region2. When hosts 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. 5 is obtained from that in Fig. 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. 5 results in the Chain in Fig. 6.

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 hosts are only moving in region1, region2, or region3 of the AP. Then the more general situation in which the hosts are moving in all of the 3 regions is considered.

### 2.1 Step 1: When All Mobile Hosts Are Only Moving in Region1 of the AP

From state transitions in Figs. 3 and 4, we can obtain the following steady state probabilities $b_{R,A,B}^s$ for a mobile host to be in states $(R, A, B)$:

$$b_{R_1,A_0^s,B_1^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_0}{W_0} b_{R_1,A_0^s,B_0^0}^0, \quad 1 \leq s \leq S - 1, 0 \leq k \leq W_0 - 1 \quad (2)$$

$$b_{R_1,A_0^s,B_1^i}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_i}{W_i} b_{R_1,A_0^s,B_i^0}^0, \quad 0 \leq i, f \leq F - 1, 0 \leq k \leq W_i - 1 \quad (3)$$

$$b_{R_2,A_0^s,B_0^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_0}{W_0} b_{R_2,A_0^s,B_0^0}^0, \quad 1 \leq s \leq S - 1, 0 \leq k \leq W_0 - 1 \quad (4)$$

$$b_{R_2,A_i^0,B_i^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_i}{W_i} b_{R_2,A_i^0,B_i^0}^0, \quad 0 \leq f \leq F - 1, 0 \leq i \leq 2F - 1, 0 \leq k \leq W_i - 1 \quad (5)$$

$$b_{R_3,A_0^f,B_0^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_0}{W_0} b_{R_3,A_0^f,B_0^0}^0, \quad 1 \leq s \leq S - 1, 0 \leq k \leq W_0 - 1 \quad (6)$$

$$b_{R_3,A_i^f,B_i^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_i}{W_i} b_{R_3,A_i^f,B_i^0}^0, \quad 0 \leq f \leq F - 1, 1 \leq i \leq m, 0 \leq k \leq W_i - 1 \quad (7)$$

$$b_{R_3,A_i^f,B_m^0}^0 = \frac{1}{1 - p_{tm}} \times \frac{W_m}{W_m} b_{R_3,A_i^f,B_m^0}^0, \quad 0 \leq f \leq F - 2, 0 \leq k \leq W_m - 1 \quad (8)$$

Based on the equations from (2) to (8), we can express all state probabilities as functions of $b_{R_1,A_i^f,B_m^0}$. Then $b_{R_1,A_i^f,B_m^0}$ is expressed in terms of $S, F,$
m, and \( p \) by using the following normalization condition:

\[
1 = \sum_{0 \leq i \leq F-1} \sum_{0 \leq f \leq F-1} W_{i-1} b_{R_1, A_j^0, B_k^0} + \sum_{s=1}^{S-1} W_0 b_{R_1, A_s^0, B_k^0} + \sum_{0 \leq f \leq 2F-1} \sum_{0 \leq f \leq F-1} W_{i-1} b_{R_2, A_j^0, B_k^0} + \sum_{s=1}^{S-1} W_0 b_{R_2, A_s^0, B_k^0} + \sum_{0 \leq i \leq m} \sum_{0 \leq f \leq F-1} W_{i-1} b_{R_3, A_j^0, B_k^0} + \sum_{s=1}^{S-1} W_0 b_{R_3, A_s^0, B_k^0} + \sum_{f=0}^{F-2} W_{m-1} b_{R_3, A_j^0, B_k^m}
\]

(9)

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

\[
p_{tx} = \sum_{0 \leq i \leq F-1} \sum_{0 \leq f \leq F-1} b_{R_1, A_j^0, B_k^0} + \sum_{s=1}^{S-1} b_{R_1, A_s^0, B_k^0} + \sum_{0 \leq f \leq 2F-1} \sum_{0 \leq f \leq F-1} b_{R_2, A_j^0, B_k^0} + \sum_{s=1}^{S-1} b_{R_2, A_s^0, B_k^0} + \sum_{0 \leq i \leq m} \sum_{0 \leq f \leq F-1} b_{R_3, A_j^0, B_k^0} + \sum_{s=1}^{S-1} b_{R_3, A_s^0, B_k^0} + \sum_{f=0}^{F-2} b_{R_3, A_j^0, B_k^m}
\]

(10)

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

\[
p = 1 - (1 - p_{tx})^{n-1}
\]

(11)

\[
p_{tm} = 1 - (1 - p_{tx})^n
\]

(12)

where \( n \) is the number of mobile hosts in the network. If Packet Error Rate (PER) needs to be considered, the \( p \) in Eq. (11) will become

\[
p^R = 1 - (1 - p_{tx})^{n-1} \times (1 - e^R)
\]

(13)

\(^*\)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.

\(^†\)A channel is said to be busy when there is at least one packet transmitted on the channel in a randomly chosen time slot.
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 [13].

Now we have an non-linear system of 4 equations, Eqs. (9)~(12), and 4 unknowns, $b_{R_1,A_0^R}, b_{R_3}, p_{tx}, p$, 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 $p^R_{tx} = \sum \text{prob. of transmission using } R$ as the conditional probability that the transmission rate is $R$, given that the host initiates a transmission on the channel, therefore:

$$
\begin{align*}
    p^R_{tx} &= \sum_{0 \leq F < F-1} b_{R_1,A_0^R} b_{R_3} + \sum_{i=1}^{S-1} b_{R_1,A_0^R} b_{R_3}^m \\
    p^R_{tx} &= \sum_{0 \leq F < F-1} b_{R_1,A_0^R} b_{R_3} + \sum_{i=1}^{S-1} b_{R_1,A_0^R} b_{R_3}^m \\
    p^R_{tx} &= \sum_{0 \leq f < F-1} b_{R_3,A_0^R} b_{R_3} + \sum_{i=1}^{S-1} b_{R_3,A_0^R} b_{R_3}^m + \sum_{f=0}^{F-2} b_{R_3,A_0^R} b_{R_3}^m \\
    p^R_{tx} &= \sum_{0 \leq f < F-1} b_{R_3,A_0^R} b_{R_3} + \sum_{i=1}^{S-1} b_{R_3,A_0^R} b_{R_3}^m + \sum_{f=0}^{F-2} b_{R_3,A_0^R} b_{R_3}^m
\end{align*}
$$

(14)

In our analysis, we do not consider the RTS/CTS technique, and the throughput at the application layer is evaluated. Let $T^R_{Succ}$ be the time needed for a successful transmission using rate $R$, then (In the followings all transmission rates are in units of Mbps, frame size has the units of bits, and time is expressed in $\mu$secs)

$$
\begin{align*}
    T^R_{Succ} &= (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_2}) + t_{DIFS} \\
    T^R_{Succ} &= (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_2}) + t_{DIFS} \\
    T^R_{Succ} &= (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_2}) + t_{DIFS}
\end{align*}
$$

(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, 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 $p^R_{Succ}$ 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:

$$
\begin{align*}
    p^R_{Succ} &= n x (p_{tx} x p_{tx}^R) x (1-p_{tx})^{n-1} \\
    p^R_{Succ} &= n x (p_{tx} x p_{tx}^R) x (1-p_{tx})^{n-1} \\
    p^R_{Succ} &= n x (p_{tx} x p_{tx}^R) x (1-p_{tx})^{n-1} \\
    \Rightarrow p^R_{Succ} &= p^R_{Succ} + p^R_{Succ} + p^R_{Succ}
\end{align*}
$$

(16)
In Eq. (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 takes place on the channel. From Eqs. (15) and (16), \( T_1^{Succ} \) is the average time needed for a successful transmission in region1:

\[
T_1^{Succ} = p_{1}^{Succ} \times T_{R_1} + p_{2}^{Succ} \times T_{R_2} + p_{3}^{Succ} \times T_{R_3} \tag{17}
\]

Let \( p_{e}^{R_i} \) be the probability that a collision occurs and the rate the slowest colliding host uses is \( R_i \), conditioned on the fact that at least one transmission occurs on the channel, therefore

\[
\begin{align*}
p_{e}^{R_1} &= \sum_{i=2}^{n} \binom{n}{i} \times (p_{tx} \times p_{tx})^{i-1} \times (1-p_{tx})^{n-i} \\
p_{e}^{R_2} &= \sum_{i=1}^{n} \binom{n}{i} \times (p_{tx} \times p_{tx})^{i-1} \times (1-p_{tx})^{n-i} \\
p_{e}^{R_3} &= 1 - p_{1}^{Succ} - p_{e}^{R_1} - p_{e}^{R_2}
\end{align*}
\] (18)

The \( p_{e}^{R_1} \) in Eq. (18) means that all \( i \) colliding hosts use rate \( R_1 \) and \( p_{e}^{R_2} \) is the probability that \( j \) out of the \( i \) colliding hosts use rate \( R_2 \) and the remaining \( i-j \) hosts use rate \( R_1 \). \( T_{e}^{R_i} \) is defined as the time spent in a collision in which the rate the slowest colliding host uses is \( R_i \), so

\[
\begin{align*}
T_{e}^{R_1} &= (t_{PLCP} + \frac{L_{MPDU}}{R_1}) + t_{DIFS} + T_o \\
T_{e}^{R_2} &= (t_{PLCP} + \frac{L_{MPDU}}{R_2}) + t_{DIFS} + T_o \\
T_{e}^{R_3} &= (t_{PLCP} + \frac{L_{MPDU}}{R_3}) + t_{DIFS} + T_o
\end{align*}
\] (19)

The \( T_o = t_{SIFS} + (t_{PLCP} + \frac{L_{ACK}}{R_{ACK}}) \) in Eq. (19) is the time that a host has to wait when its frame transmission collides, before sensing the channel again. From Eqs. (18) and (19), we can obtain the average time spent in a failed transmission in region1 as follows:

\[
T_{e} = p_{e}^{R_1} \times T_{e}^{R_1} + p_{e}^{R_2} \times T_{e}^{R_2} + p_{e}^{R_3} \times T_{e}^{R_3} \tag{20}
\]

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

\[
Th_1 = \frac{E[\text{user bits transmitted in a time slot}]}{E[\text{length of a time slot}]} = \frac{p_{tr} \times p_{1}^{Succ} \times L_{App}}{(1 - p_{tr}) \times \sigma + p_{tr} \times T_1^{Succ} + p_{tr} \times T_{e}} \tag{21}
\]

where \( L_{App} \) is the packet size at the application layer and \( \sigma \) is the idle slot time.
Table 1: The parameters used in simulations and analytical model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmit Power</td>
<td>15 dBm</td>
</tr>
<tr>
<td>$R_1/R_2/R_3/R_{ACK}$</td>
<td>11.0/5.5/1.0/1.0 Mbps</td>
</tr>
<tr>
<td>$d_{min}/d_1/d_2/d_3 = d_{max}$</td>
<td>0/399/531/796 meters</td>
</tr>
<tr>
<td>Receive Threshold of $R_1/R_2/R_3$</td>
<td>-82/-87/-94 dBm</td>
</tr>
<tr>
<td>Propagation Model</td>
<td>Two Ray Ground</td>
</tr>
<tr>
<td>Link Propagation Delay</td>
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</tr>
<tr>
<td>Packet Error Rate $e^{R_1}$, $e^{R_2}$, and $e^{R_3}$</td>
<td>0</td>
</tr>
<tr>
<td>$\sigma/t_{DIFS}/t_{SIFS}/t_{PLCP}$</td>
<td>20/50/10/192 µsecs</td>
</tr>
<tr>
<td>$W_{min/m}$</td>
<td>31/5</td>
</tr>
<tr>
<td>$L_{MPDU}/L_{ACK}$</td>
<td>11712/12160/112 bits</td>
</tr>
<tr>
<td>Simulation Time</td>
<td>10000 sec</td>
</tr>
</tbody>
</table>

2.2 Steps 2 and 3: When All Mobile Hosts Are Only Moving in Region2 or Region3 of the AP

Since the Markov Chains for hosts moving in region2 or region3 of the AP are obtained from those of region1, the saturation throughput $T_{h2}/T_{h3}$ when all hosts are only moving in region2/region3 of the AP can be easily obtained by following the same procedures as those in Sec. 2.1. Thus the expressions for $T_{h2}$ and $T_{h3}$ have the same form as that in Eq. (21).

2.3 Step 4: The General Situation

Now we consider the general situation in which the hosts are moving between the minimum distance $d_{min} = 0$ and maximum distance $d_{max} = d_3$ from the AP, that is to say: the hosts 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 a host and the AP can be considered to be uniformly distributed in the range $[0, d_3]$. Therefore

$$Th = \frac{d_1}{d_3} \times Th_1 + \frac{d_2 - d_1}{d_3} \times Th_2 + \frac{d_3 - d_2}{d_3} \times Th_3$$  \hspace{1cm} (22)

3 Model Validation

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
Figure 7: Saturation throughput: simulation versus analysis for various ARF parameters and numbers of mobile hosts.

Figure 8: The saturation throughput for hosts moving in all 3 regions of the AP.
results are summarized in Table 1 which are also used in [7, 8]. The network environment in Fig. 2 is also considered in simulations. In simulations, the hosts in the network are considered to move back and forth between the minimum distance of $d_{\text{min}} = 0$ and maximum distance of $d_{\text{max}} = 796$ 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. 7. From this figure, we can see that the analytical results match very well with the simulation results, so our model can be justified. For the purposes of comparing the throughput performance, the same results are also shown in Fig. 8. From these results, we can say that in order for a network to have better throughput performance, a smaller $S$ and a larger $F$ than those used in [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 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 [9] 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 to 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 have a smaller value so that the host can use the most appropriate transmission rate earlier will also benefit the network throughput.

4 Delay Analysis

Based on the proposed model, we will in this section perform the delay analysis, and this analysis will be conducted in the same manner as that for throughput analysis. As in [2], packet delay is defined as the time interval between the generation of a packet and the successful of its reception. Let $D_i$ be the random variable denoting the packet delay and $E[D_i]$ the mean of the delay for hosts moving in the $i$th region of the AP, where $i = 1, 2, 3$. Then

$$E[D_i] = E[C_i] \times (E[B_i] + T_i^c) + (E[B_i] + T_i^{\text{Succ}})$$

‡Recall that the ARF parameters $S$ and $F$ used by WaveLAN-II devices are 10 and 2, respectively.
Figure 9: Saturation delay for various ARF parameters and number of mobile hosts.
where \( (1) \) \( E[C_i] = \frac{1}{p_i^{\text{succ}}} - 1 \) is the average number of failures of a packet until its successful reception, and \( p_i^{\text{succ}} \) is the probability of successful transmission for hosts moving in the \( i \)th region of the AP; \( (2) \) \( E[B_i] \) is the average time of the backoff delay; and \( (3) T_i^{\text{succ}}/T_i^e \) is the time needed for a successful/failed transmission. The expressions for \( p_i^{\text{succ}}, T_i^{\text{succ}}, \) and \( T_i^e \) are given in Eqs. (16), (17) and (20), respectively. Those for \( i=2 \) and \( 3 \) are as follows:

\[
\begin{align*}
    p_2^{\text{succ}} &= p_2^{R_2} + p_3^{R_3} \\
    T_2^{\text{succ}} &= p_2^{R_2} \times T_2^{R_2} + p_3^{R_3} \times T_3^{R_3} \\
    T_2^e &= p_2^{R_2} \times T_e^{R_2} + p_3^{R_3} \times T_e^{R_3} \\
    p_3^{\text{succ}} &= p_3^{R_3} \\
    T_3^{\text{succ}} &= p_3^{R_3} \times T_3^{R_3} \\
    T_3^e &= p_3^{R_3} \times T_e^{R_3}
\end{align*}
\] (24)

Let \( X_i \) be the random variable representing the time needed for a host in state \( (R, A_i^l, B^l) \) to reach the transmission state \( (R, A_i^l, B_0^l) \), excluding the time when the backoff counter is frozen. Then, the average of this time interval, in time slots, is:

\[
E[X_i] = \sum_{0 \leq f \leq F-1} W_{f-1} \sum_{0 \leq k \leq F-1} k \times b_{R_1, A_i^l, B^l_k} + \sum_{s=0}^{S-1} W_0 \sum_{0 \leq k \leq F-1} k \times b_{R_1, A_0^l, B_0^l_k} + \sum_{s=1}^{S-1} W_0 \sum_{s=1}^{S-1} k \times b_{R_2, A_i^l, B^l_k} + \sum_{s=0}^{S-1} W_0 \sum_{s=1}^{S-1} k \times b_{R_2, A_0^l, B_0^l_k} + \sum_{s=1}^{S-1} W_0 \sum_{s=1}^{S-1} k \times b_{R_3, A_i^l, B^l_k} + \sum_{s=0}^{S-1} W_0 \sum_{s=1}^{S-1} k \times b_{R_3, A_0^l, B_0^l_k}
\] (25)

Denoting \( E[Z_i] \) as the average number of times that a host in the \( i \)th region of the AP senses a busy channel before reaching the transmission state, then

\[
E[Z_i] = \frac{E[X_i]}{\max(E[Y_i], 1)} - 1
\] (26)

where \( E[Y_i] = \frac{1}{p_{tm}} - 1 \) 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 \( E[N_i] = E[Z_i] \times (p_i^{\text{succ}} \times T_i^{\text{succ}} + (1 - p_i^{\text{succ}}) \times T_i^e) \) is the average time, in \( \mu \)sec, that the backoff counter of a host is stopped and \( \sigma \) is the time period, in \( \mu \)sec, of an idle time slot.
Finally, the average packet delay, in \( \mu \)secs, for hosts moving in all 3 regions of the AP can be calculated as follows:

\[
E[D] = \frac{d_1}{d_3} \times E[D_1] + \frac{d_2 - d_1}{d_3} \times E[D_2] + \frac{d_3 - d_2}{d_3} \times E[D_3]
\] (27)

The analytical and simulation results are shown in Fig. 9(a)~(c) for various ARF parameter values and numbers of mobile hosts. From Fig. 9(d), we can say 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.

5 Conclusions

In this paper, we have presented an analytical model to evaluate the saturation throughput and delay performance of the 802.11 DCF in an environment in which the mobile hosts have multi-rate support and will use ARF to change the rates to adapt to different channel conditions. Although some previous works have studied the performance of a WLAN with hosts 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 ARF parameter \( S \) and a larger \( F \) 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 correspond more closely to the real situation.

References


