System Throughput Maximization Subject to Delay and Time Fairness Constraints in 802.11 WLANs

Yean-Fu Wen, Frank Yeong-Sung Lin, and Kun-Wei Lai
Department of Information Management, National Taiwan University (NTU)
{*d89002*; *yslin*; *r91006*}*@im.ntu.edu.tw*

Abstract

It is difficult to achieve a trade off between system throughput fairness and channel access time fairness in 802.11Wireless Local Area Networks (WLANs). The reason is that, under the multiple rate wireless protocol, a lower bit rate host penalizes hosts that use a higher bit rate with throughput fairness. In this paper, we propose a contention-based MAC (Media Access Control) protocol for data communications in WLANs that achieves access time near-fairness and maximizes the aggregate throughput with simultaneous delay bound. Our suggested parameter values would help manufacturers and carriers of protocol configurations improve system throughput. This approach utilizes initial contention windows, packet size, and multiple back-to-back packets as decision variables. To evaluate our approach, we use an extended analytical model, which has been shown to be a non-linear dynamic integer problem. However, the experiment results show that a packet's size and initial contention windows form a simple unimodal distribution to achieve access time near-fairness, which tends to maximize the packet's size and increase the initial contention windows. Thus, we use a simple binary search to determine the composition of the initial contention windows, packet size, and multiple back-to-back packets. The system throughput increases as the number of packets in a block increases, but the delay also monotonically increases. We therefore consider the delay bound in order to limit the number of packets in a block. To evaluate our model, we use NS2 as a simulation tool. The results show that our model is accurate and that system throughput is maximized, subject to delay and time fairness.

1. Introduction

Although a wireless network provides free Internet retrieval, the bandwidth is lower than that of a traditional wired network. Our goal is to improve the bandwidth to meet the demands of various applications. Although the current states of WLANs are 802.11b [3], 802.11g [4], and 802.11a [2], with the highest rate of 11Mbps, 54Mbps, and 54Mbps respectively, they have two major defects in that the fluctuating bit rates are subject to: 1) signal fading, and 2) interference. Furthermore, overhead and media sharing have lower bit rates than the theoretical bandwidth for an individual host. The wired Ethernet protocol based on CSMA/CD (Carrier Sense Multiple Access with Collision Detection) is known to be fair. However, its wireless counterpart, 802.11b, based on CSMA/CA with various bit rates has proved to be unfair [15]. We therefore propose a parameter reconfiguration approach to maximize system throughput within a delay bound to achieve access time near-fairness. This would help manufacturers and carriers of system configurations improve system throughput.

Some works, [5], [6], [11], [12], [19], and [26], address the long-term time fairness issue and provide uplink and downlink solutions. G. Tan et al. introduce the concept of a downlink solution with queuing control [11] and an uplink solution with packet size or burst packets [12]. Unfortunately, they do not provide the real values of these parameters. The fairness control of the downlink solution is controlled by the AP (Access Point). In [6] and [19], the authors adopt NS2 to simulate a high quality signal with multiple back-to-back packets that can improve system throughput. In our previous work [26], the uplinks solution focused on the DCF mechanism parameters, including packet size and initial contention windows. Here, we not only consider system throughput, but also focus on the delay issue. We determine the relationship between these parameters, and provide the parameter combinations to achieve maximum system throughput.

Since our objective is to achieve access time near-fairness of DCF under 802.11 WLAN, we find that the initial contention window (W_k), packet size (L_k), and multiple back-to-back packets (B_k) are the most important variables that affect system throughput and access time in a multi-rate environment.

1.1 Initial contention windows (W_k)

Many researchers have proposed modified back-off mechanisms, such as initial contention windows, CW_{min}, *cw* incremental value, and various intervals (CW_{min}, CW_{max}) to provide QoS and differential services [7] [24]. Although these mechanisms do not address the issue of access time

Proceedings of the 2005 11th International Conference on Parallel and Distributed Systems (ICPADS'05)
0-7695-2281-5/05 $20.00 © 2005 **IEEE**

fairness, we use the same concepts to achieve such fairness. The most common fairness problem is the short-term back-off effort, caused by back-off trigger and recovery [17], [21], and [22]. Although some approaches [8] and [14] try to reduce the number of collisions, they focus on the unfair shortened back-off effect and do not consider access time fairness issues. Heusse et al. [15] point out that in some common situations in a wireless environment, channel access probability fairness causes considerable performance degradation. They, however, only describe the serious problem of channel access fairness with a multi-rate MAC protocol, without suggesting any solutions. In this paper, we focus on achieving long-term access time fairness solutions.

1.2 Packet size (L_k)

J. Jelitto et al. [14] surveyed the relation between packet length and bandwidth. As expected, the bandwidth increases with increasing frame length. This, however, does not mean that the frame length can be increased because, at the MAC layer, we have to consider the limitation of the upper layer and Ethernet. For this reason, and in line with standards [1], [2], [3], and [4], we limit our frame size to 1,500 bytes and 2,304 bytes for the basic mode and RTS/CTS mode respectively.

1.3 Multiple back-to-back packets (B_k)

The decision variable B_k is used to set the transmission cycle time based on the slowest MHs (i.e., those that transmit one packet per cycle). In the multiple packets approach, an MH is allowed to send multiple frames consecutively by setting *more_frag* = 1 in the MAC control frame after gaining access to the medium [9]. The throughput performance of a similar approach for 802.11b is studied in [19], [25]. Sadeghi et al. [6] also introduce the Opportunistic Auto Rate (OAR), an enhanced protocol for multi-rate IEEE 802.11 in wireless ad hoc networks. The main issue here is that an MH can monopolize the medium and starve out all other MHs. To avoid this starvation problem, we utilize multiple back-to-back packets to limit the delay bound.

The remainder of this paper is organized as follows. In Section 2, we analyze the problem with an analytical model and mathematical equations. In Section 3, we propose an algorithm for problem solving based on the initial numerical results. In Section 4, the maximum system throughput with delay bound for achieving access time near-fairness and the performance evaluation are simulated and calculated with NS2 and Matlab tools respectively. Finally, in Section 5, we present our conclusions.

2. Analytical model

We modify and extend Bianchi's model [10] to limit the back-off time to a finite state for block ACK with an AP. A two- or four-way handshaking mechanism is adopted in the MAC protocol. Tables 1, 2, and 3 respectively list the main notations and descriptions, the given parameters, and the decision variables in our extended analytical model.

2.1 Markov analysis

We begin by estimating the probability of a collision. Let $p(t)$ denote the collision probability when a packet is being transmitted at time t. Assume that $p(t)$ is constant and independent of time, i.e., $p(t) = p$ for all integers $t \geq 0$. Let $S(t)$ denote the back-off stage at time t, where $0 \leq S(t) \leq m + u$. Figure 1 shows the finite state of the back-off Markov chain. Its probability distribution is calculated by

$$\Pr\{S_k = s\} = \begin{cases} \dfrac{1-p_k}{1-p_k^{m+u+1}} & \text{if } s = 0; \\ \dfrac{1-p_k}{1-p_k^{m+u+1}}\, p_k^s & \text{if } 1 \leq s \leq m+u; \\ 0 & \text{if } s > m+u. \end{cases} \quad (1)$$

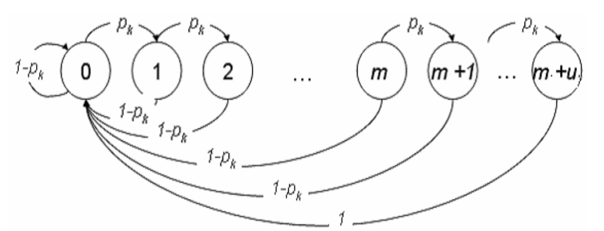

Figure 1. Finite state of the back-off Markov chain

Table 1. Main notations

Notation	Descriptions
p_k	Collision probability of a class-*k* station.
q_k	Packet transmission probability of a class-*k* station.
f_k	The average fraction of time occupied by a class-*k* station, $0 \leq f_k \leq 1$.
ε	The minimal value, where $\varepsilon < 10^{-6}$.
ρ_k	The saturation bandwidth for traffic class-*k* stations.
κ_k	The probability that a class-*k* packet will be successfully transmitted during a transmission cycle.
$E[P_k]$	The average number of bits successfully transmitted for a class-*k* station during a transmission cycle.
$E[T_I]$	The average time of all idle periods.
$E[T_C]$	The average time of all collision periods.
$E[T_S]$	The average time of successful transmission during a transmission cycle.
$E[T_k]$	The average time of a transmission cycle for a class-*k* station.
$E[T_{S,k}]$	The average time for a class-*k* station to successfully transmit a packet during a transmission cycle..
N_c	The number of collisions in a transmission cycle.
p_c	The collision probability when a mobile station is transmitting a packet.
d_k	The amount of time required by a class-*k* station to hold a channel.
N_s	The number of time slots in an idle period.
η_s	The back-off counter in back-off stage *s*.

Table 2. Given parameters

Notation	Descriptions
r	The number of classes with a distinct bit rate in the system, where $r \geq 1$.
n_k	The number of MHs that belong to class-k, where $1 \leq k \leq r$.
m	The maximum number of back-off stages.
u	The remaining number of trials after the cw exceeds CW_{max}.
D	The maximum channel access time for each MH.
R_k	The bit rate of a class-k station.
T_{pro}	The propagation delay for all packets.
δ	Slot time.
T_{DIFS}	DIFS time.
T_{SIFS}	SIFS time.
T_{ACK}	ACK time.
L_{min}, L_{max}	The minimal and maximal packet sizes.
W_{min}, W_{max}	The minimal and maximal initial contention window sizes.
B_{max}	The maximum number of multiple back-to-back packets.
TFI	Time Fairness Index, $0 \leq TFI \leq 1$.
T_{RTS},	The time required to transmit an RTS frame, including a physical layer header and a MAC header.
T_{CTS}	The time required to transmit a CTS frame, including a physical layer header and a MAC header.
T_{PHY}	The time required to transmit a physical layer header.
T_{MAC}	The amount of time required to transmit a MAC header.

Table 3. Decision Variables

Notation	Descriptions
W_k	The suggested initial contention windows value of a class-k station.
L_k	The suggested packet size (MSDU) of a class-k packet.
B_k	The suggested number of multiple back-to-back packets of class-k in a block within a transmission cycle.

Then, the distribution of $\eta_{k,s}$ is calculated by

$$\Pr\{\eta_{k,s} = i\} = \Pr\{\eta_k = i \mid S_k = s\}$$

$$\begin{cases} \dfrac{1}{2^s W_k}, & \text{for } i = 0,\ 1,\ 2, \cdots, 2^s W_k - 1; \quad 0 \leq s \leq m-1 \\ \dfrac{1}{2^m W_k}, & \text{for } i = 0,\ 1,\ 2, \cdots, 2^s W_k - 1; \quad m \leq s \leq m+u \end{cases} \tag{2}$$

Since the back-off counter follows a uniform distribution, the mean value of η_k with the condition probability at state s is

$$E[\eta_k \mid S_k = s] = \begin{cases} \dfrac{2^s W_k - 1}{2}, & 0 \leq s \leq m-1 \\ \dfrac{2^m W_k - 1}{2}, & m \leq s \leq m+u \end{cases} \tag{3}$$

Then, taking the sum of all the probabilities of (2) and multiplying it by (3), we get the average number of η for all back-off states by (4).

In a steady state, the transmitting station has to wait $E[\eta]$ logical time before it can transmit a packet. The probability that q will transmit a packet at any logical time is calculated by (5).

The probability of one or more other stations transmitting packets at the same logical time follows a geometric distribution, so we get (6).

2.2 Throughput analysis

We can now derive expressions for performance measures, such as system throughput and average access delay in a channel. The saturation throughput of the DCF access method has been extensively studied in recent literature [9], [10], [13], [16], and [23]. We assume that the time lengths of all transmission cycles are independently and identically distributed. Suppose that the system wins a reward, which is the number of bits successfully transmitted, after a successful transmission. Let $R_k(t)$ denote a renewal reward process that represents the reward earned by traffic class-k from time zero to time t. Figure 2 shows the renewal and reward transmission cycle, including the idle, collision, and success periods. An idle period is a time interval in which the channel remains idle due to the back-off procedure. The success period, T_s, denotes that a sender has successfully received an ACK. Here, we add-in the multiple back-to-back packets parameter B_k, which denotes the number of multiple packets transmitted by class-k MHs during the transmission cycle.

According to the IEEE 802.11 specifications [1], T_s for the basic mode and the RTS/CTS mechanism can be calculated by (7). The collision time, T_c, can be computed by (8) for the basic and the RTS/CTS modes. Then, the saturation bandwidth for class-k stations is (9). The average successful transmission bit rate can be calculated by

$$E[P_k] = \kappa_k B_k L_k , \tag{10}$$

So, the equation of K_k is as follows:

$$\kappa_k = \frac{n_k q_k (1-q_k)^{n_k - 1} \prod_{j=1, j\neq k}^{r} (1-q_j)^{n_j}}{\sum_{i=1}^{r} n_i q_i (1-q_i)^{n_i - 1} \prod_{j=1, j\neq i}^{r} (1-q_j)^{n_j}} \tag{11}$$

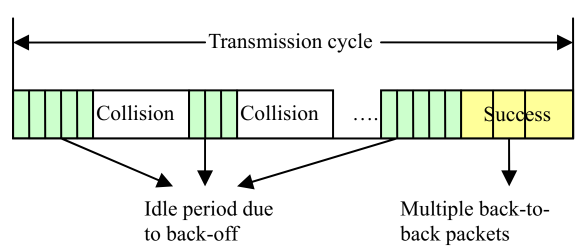

Figure 2. Renewal and reward transmission cycle

$$E[\eta] = \sum_{s=0}^{m+u} E[\eta_k \mid S_k = s]\Pr\{S_k = s\} = \frac{(1-2p_k)(W_k - 1 - 2^m p_k^{m+u+1} W_k + p_k^{m+u+1}) + p_k W_k (1-(2p_k)^m)}{2(1-2p_k)(1-p_k^{m+u+1})} \quad (4)$$

Note that Bianchi evaluated $p_k < 0.5$ to avoid zero error, which could be caused by the partial equation (1 - 2p_k) [10].

$$q_k = \frac{1}{E[\eta]+1} = \frac{2(1-2p_k)(1-p_k^{m+u+1})}{(1-2p_k)(W_k + 1 - 2^m p_k^{m+u+1} W_k - p_k^{m+u+1}) + p_k W_k (1-(2p_k)^m)} \quad (5)$$

$$p_k = 1 - (1-q_k)^{n_k - 1} \prod_{1 \le j \le r, j \ne k} (1-q_j)^{n_j} \quad (6)$$

$$E[T_s] = \begin{cases} B_k(T_{PHY} + T_{MAC} + \sum_{i=1}^{r} E[P_i]/R_i + T_{pro} + T_{SIFS} + T_{ACK}) + T_{DIFS} & \text{for the basic mode} \\ T_{RTS} + 2T_{SIFS} + T_{CTS} + B_k * (T_{SIFS} + T_{pro} + T_{PHY} + T_{MAC} + \sum_{i=1}^{r} E[P_i]/R_i + T_{SIFS} + T_{pro} + T_{ACK}) + T_{DIFS} & \text{for the RTS/CTS mode} \end{cases} \quad (7)$$

$$T_c = \begin{cases} E[N_c]T_s & \text{for the basic mode} \\ E[N_c](T_{DIFS} + T_{RTS} + T_{SIFS} + T_{CTS}) & \text{for the RTS/CTS mode} \end{cases} \quad (8)$$

$$\rho_k = \lim_{t\to\infty} \frac{R_k(t)}{t} = \frac{E[P_k]}{E[T_I + T_C + T_S]} = \frac{E[P_k]}{E[T_I] + E[T_C] + E[T_S]} \quad (9)$$

Assume that θ_c is the collision probability when a mobile station is transmitting a packet. If θ_c can be computed by at least one transmitting stations, then θ_c is:

$$\theta_c = \frac{1 - \prod_{j=1}^{r}(1-q_j)^{n_j} - \sum_{i=1}^{r} n_i q_i (1-q_i)^{n_i - 1} \prod_{j=1, j\ne i}^{r} (1-q_j)^{n_j}}{1 - \prod_{j=1}^{r}(1-q_j)^{n_j}} \quad (12)$$

The distribution of N_c follows a geometric distribution and yields

$$E(N_c) = \theta_c / (1-\theta_c) \quad (13)$$

We assume that the time lengths of idle periods are independently and identically distributed. Then T_I can then be computed as

$$E[T_I] = (E[N_c]+1)(\delta E[N_s]) \,. \quad (14)$$

The distribution of N_s also follows a geometric distribution and the mean value of N_s is as follows:

$$E[N_S] = \left(\prod_{j=1}^{r} (1-q_j)^{n_j} \middle/ 1 - \prod_{j=1}^{r} (1-q_j)^{n_j} \right) \quad (15)$$

2.3 Fairness index

To prove that our approaches achieve access time near-fairness, we adopt the fairness index techniques in [18]. We obtain an individual MH's access time from each class access time f_k divided by the number of MHs belonging to that class. The *TFI* equation is

$$TFI = \left(\sum_{k=1}^{r} n_k \left(\frac{f_k}{n_k}\right) \right)^2 \middle/ \sum_{k=1}^{r} n_k \left(\sum_{k=1}^{r} n_k \left(\frac{f_k}{n_k}\right)^2 \right) \quad (16)$$

Finally, we list our objective function Z_{IP} and constraints (17) to (23) as follows:

$$Z_{IP} = \max \sum_{k=1}^{r} \frac{E[P_k]}{E[T_I] + E[T_C] + E[T_S]} \quad (17)$$

subject to

$$(1-\varepsilon) < TFI <= 1 \quad (18)$$

$$d_k \le D \qquad k = 1, ..., r \quad (19)$$

$$L_{\min} \le L_k \le L_{\max} \qquad k = 1, ..., r \quad (20)$$

$$W_{\min} \le W_k \le W_{\max} \qquad k = 1, ..., r \quad (21)$$

$$1 \le B_k \le B_{\max} \qquad k = 1, ..., r \quad (22)$$

$$B_k, L_k, W_k \text{ are integers} \qquad k = 1, ..., r \,. \quad (23)$$

The objective function maximizes system throughput, subject to

Constraint (18) Find the *TFI* value close to 1, which means that time fairness has been achieved.

Constraint (19) Limit each MH transmission time to a given period.

Constraint (20) Limit the L_k so that it is larger than L_{min}, but smaller than L_{max}.

Constraint (21) Limit the W_k so that it is larger than W_{min}, but smaller than W_{max}.

Constraint (22) Limit the B_k parameter value so that it is larger than or equal to 1, but less than B_{max}.

Constraint (23) Enforce decision variables B_k, L_k, and W_k to fulfill the integer constraint.

3. Proposed algorithm

Exhaustive search is one method for finding the system throughput with a combination of W_k, L_k, and B_k for each transmission bit rate class, but it is hard because solving the problem size $\prod_{k=1}^{r} B_k \cdot L_k \cdot W_k$ requires too much computing time. Consequently, we try to find the break-point for the exhaustive search loop. In order to achieve access time fairness, we first consider the W_k and L_k decision variables modifications and then compare system throughput. As, according to (18), the *TFI* value is approximately 1 with deviation less than ε, we compare the system throughput, but only record the maximum throughput to achieve our objective function. Figure 3 shows the maximum system throughput (which tends to increase the L_k as much as possible) when the value of W_k increases and all *TFI*s are approximately 1. On the other hand, we can set the L_k to L_{max}, and then modify the W_k value to achieve access time near-fairness first. As the improvement is limited by the W_k variable, we modify the L_k to fix the *TFI* value closer to 1.

Figure 4 shows the modified W_k value versus the *TFI* value. The *TFI* values form a unimodal curve even when we change the composition of the MHs (i.e., a mixture of fast and slow MHs). The W_k values are limited by constraints (21) and (23) respectively, which means we can find the *TFI* value that approximates to 1 by a simple binary search. After tuning the W_k value, the L_k is tuned so that the *TFI* value is closer to 1. Figure 5 shows that the L_k versus the *TFI* equal to 1 forms a unimodal curve. This is similar to W_k with different numbers of MHs, which means that we can also obtain a near-optimal L_k composition by a binary search. The algorithm for finding the W_k value for *TFI* close to 1 is shown in Figure 7. The L_k can be found by the same algorithm.

We use the same method to analyze the number of packets in a block. Figure 6 shows that if we maintain the number of packets in a block, the *TFI* curve shifts horizontally. If the number of packets for a faster MH is increased, the *TFI* curve shifts to the right. Conversely, the *TFI* curve shifts to the left, if the number of packets for a slower MH is increased. Since the value B_k in a block is limited by (22), we can use a sequential search to find the optimal number of packets in a block.

To achieve access time fairness, we utilize Jain's *FI* as a reference point for tuning the W_k, L_k, and B_k, decision variables. The W_k and L_k variables, which can be tuned sequentially, have an important unimodal feature that can find the optimal composition by a simple binary search. We adopt a sequential search to find the B_k variable with delay bound to limit the size of B_k. Accordingly, the time complexity is $O(B_{max}^4(\varphi\, CW_{max}\sqrt{CW_{max}} + L_{max}\sqrt{L_{max}}))$, where φ is the time complexity used to solve p and q simultaneous equations.

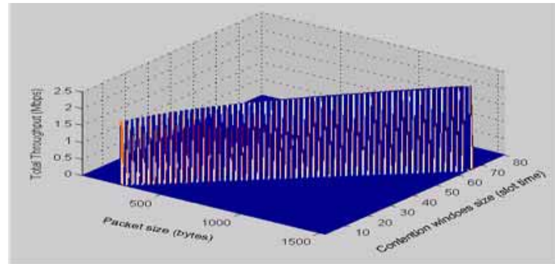

Figure 3. Tuning W_k and L_k to achieve maximum system throughput

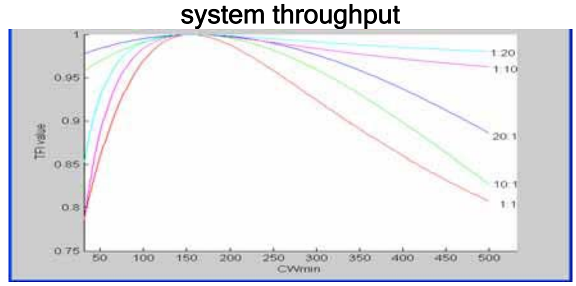

Figure 4. The TFI versus W_k forms a unimodal curve

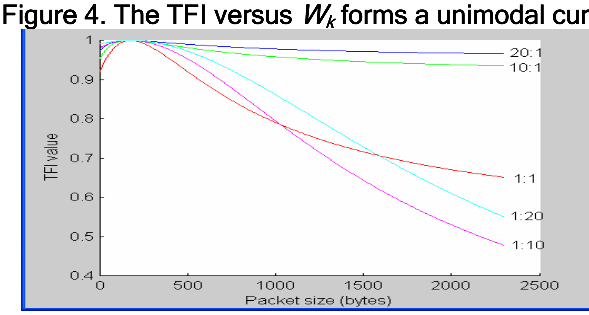

Figure 5. The *TFI* versus the packet size forms a unimodal curve

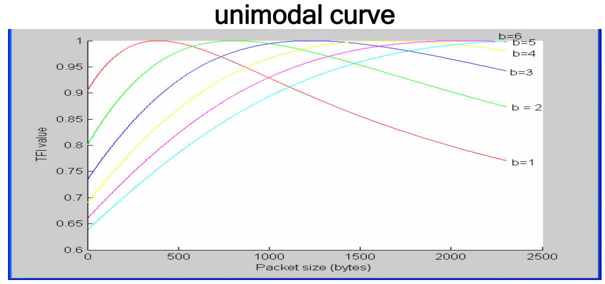

Figure 6. The *TFI* distributions by changing the B_k in a block

4. Performance evaluation and simulations

In this section we evaluate our extended analytical model by NS2 simulation. We also give some examples of W_k, L_k, and B_k composed of various numbers of nodes, such as maximum system throughput, maximum system throughput with delay bound, and average delay. Table 4 lists the parameter values used for evaluation in the 802.11b standard specification [9].

4.1 Evaluation of the extended analytical model

We use NS2 simulation tools [20] to evaluate our analytical model. Figure 8 shows that the system throughput and the *TFI* versus the number of MHs achieve the same results by simulation or numerical analysis. Each point on the numerical curve is derived by the Matlab tools of our algorithm. Meanwhile, each point on the simulation curve is taken from the NS2 simulation tool of a 1,000 second simulation time. The figure also shows that throughput increases when we add two higher MHs (i.e., 11Mbps MHs) to the system (which already has one 2Mbps MH) for each point on both the "AM11" and the "ns2-11" curves. Conversely, system throughput decreases when we increase the number of lower MHs (i.e., 2Mbps MHs) in the system (which already has one 11Mbps MH) for each point on both the "AM2" and "ns2-2" curves. The *TFI* values of the results shown in Figure 8 (see "TFI-11" and "TFI-2" curves) are almost equal to 1. Thus, the results fulfill the time fairness condition and show that our analytical model is accurate.

4.2 Maximizing system throughput with delay bound

Our objective function maximizes system throughput, which increases as the third decision variable's B_k value increases monotonically. However, multiple back-to-back packets hold the channel time longer than the original mode [25]. We therefore consider that the delay bound limits the number of packets in a block.

```
Algorithm Binary_Search_CWmin_or_L( n[], L[], R[], W_min[], W_max[])
Input: Given the number of MHs n[], contention window W_min[] and
        W_max[], packet size L[], and bit rates R[],
Output: the W_k or packet size L_k for each class of TFI close to 1.
For i = 0 to W_max - 31        // W_max is set to 1023.
    w(highest_rate) = W_min + i;
    Initial cw for highest bit rate class MH and High_w, Low_w equal
            to W_min, W_max respectively.
    Setting the current cw to the middle between High_w and Low_w.
    While (High_w - Low_w) > 1
        Calculate the probability of idle, collision, etc. Then, adopt a
              geometric distribution to compute Nc, Ns.
        Calculate E[P], T_c, T_i, f_k etc. Then iterate these values by (16) to
              get the TFI value.
        For each class of MHs
            If fi(i) > fi(highest_rate)
               low_w(i) = w(i);
            Else
               high_w(i) = w(i);
            End-If
            w(i)=round((low_w(i)+ high_w(i))/2);
        End-For
    End-While
    Calculate the System Throughput.
    If the Throughput does not improve at all
        Exit for-loop.
    End-If
End-For.
```

Figure 7. The algorithm for optimal W_k and packet size L_k combination for achieving *TFI* = 1

Table 4. Parameter values used for evaluation

Parameters	Values	Parameters	Values
MSDU size	1500bytes	ACK length	14bytes
MAC header	34bytes	PHY header	16bytes
RTS payload	20bytes	CTS payload	14bytes
Slot time	20µs	DIFS	50µs
SIFS	10µs	Propagation time	1µs
CW_{min}	31	CW_{max}	1023
L_{max}	2304	B_{max}	11

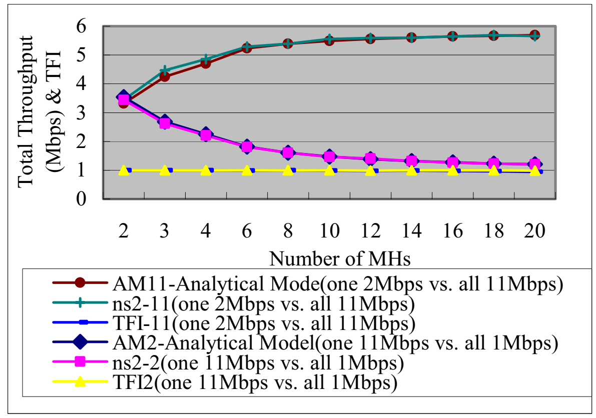

Figure 8. Analytical model evaluation by NS2

We use our heuristic algorithm to find the maximum system throughput that achieves time near-fairness. When we join the number of packets in a block B_k decision variable, we find the combination of W_k, L_k, and B_k that yields the maximum system throughput that achieves time near-fairness. Table 5 shows the combinations which are the numerical results for each class with a different number of MHs. Since the number of packets in a block is constrained by the delay, we use a sequential search with a simple guard method to break the for-loop execution. The results show that W_k is usually adjusted to achieve time fairness close to 1. In addition, the number of packets in a block and the packet size tend to be maximized for the fastest class of MHs, while the other classes adjust their composition to achieve a *TFI* value more approximate to 1. As the number of packets increases for faster MHs, W_k decreases for slower MHs.

5. Conclusions

In this paper, an analytical model is extended to maximize system throughput with delay bound under channel access time fairness. The simulation results show that our model is accurate. Though the problem has been shown to be NP-complete, our numerical results reveal a simple unimodal feature, which can be solved with a binary search for the L_k and W_k when the *TFI* is close to 1. An important requirement for finding the maximum system throughput under time fairness is that, initially, the L_k must approach the maximum length and the W_k must be tuned to achieve a *TFI* value approximate to 1. The L_k for each class is then tuned to achieve a *TFI* value closer to 1.

As we consider the delay bound with the B_k variable, which limits the monotonically increasing system throughput and delay, we adopt a sequential search to find the optimal number of packets in a block. Therefore, the composition of the three decision variables can be solved. This would help manufacturers and carriers of protocol configurations improve system throughput.

References

[1] ANSI/IEEE, IEEE Standard 802.11, 2000.

[2] ANSI/IEEE, IEEE Standard 802.11a, 1999.

[3] ANSI/IEEE, IEEE Standard 802.11b, 1999.

[4] ANSI/IEEE, IEEE Standard 802.11g/D3.0, 2002.

[5] A. Munaretto, M. Fonseca, K. A. Agha, and G. Pujolle, "Fair Time Sharing Protocol: a Solution for IEEE 802.11b Hot Spots", IFIP/IEEE ICT 2004, pp. 1261-1266.

[6] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knighlty, "Opportunistic media access for multi-rate ad hoc networks", Proc. of ACM MobiCom'02, Atlanta, Giorgia, Sept. 2002.

[7] D.J. Deng and R.S. Chang, "A priority scheme for IEEE 802.11 DCF access method", *IEICE Trans. Comm.*, E82-B(1), Jan. 1999.

[8] F. Calì, M. Conti , E. Gregori, "Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit', *IEEE/ACM Transactions on Networking*, 8(6), 2000, pp. 785-799.

[9] G. Bianchi, "IEEE 802.11: saturation throughput analysis', *IEEE Comm. Letters,* 2(12), 1998, pp. 318-320.

[10] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function", *Selected Areas in Comm., IEEE Jou. on,* 18(3), 2000, pp. 535-547.

[11] G. Tan and J. Guttag, "Time-based fairness improves performance in multi-rate WLANs", Proc. of USENIX'04, Boston, MA, June 2004.

[12] G. Tan and J. Guttag, "Long-term Time-share Guarantees are Necessary for Wireless LANs", Proc. of SIGOPS European Workshop, Leuven, Belgium, Sept. 2004.

[13] G. Wang, Y. Shu, L. Zhang, O.W.W. Yang, "Delay analysis of the IEEE 802.11 DCF", Proc. of IEEE PIMRC, Beijing, China, Sep. 2003.

[14] J. Jelitto, H. L. Truong, "A multi-MAC approach to overcome the throughput limits of 802.11 WLANs", 2004 International Zurich Seminar, Feb. 2004, pp. 32-35.

[15] M. Heusse; F. Rousseau, G. Berger-Sabbatel, A. Duda, "Performance anomaly of 802.11b", IEEE INFOCOM 2003, 2(30), Apr. 2003, pp. 836-843.

[16] N. Gupta and S. R. Das. "A capacity and utilization study of mobile ad hoc networks". Proc. of 26th Annual IEEE Conference on LCN 2001, Nov. 2001, pp. 576-583.

[17] P. Karn, "MACA-a new channel access method for packet radio", Proc. of 9th ARRL Computer Networking Conference, 1990.

[18] R. Jain, W. Hawe, D. Chiu, "A quantitative measure of fairness and discrimination for resource allocation in Shared Computer Systems", DEC Research Report TR-301, 1984.

[19] S. T. Sheu, T. Chen, J. Chen, F. Yu, "An improved data flushing MAC protocol for IEEE 802.11 wireless ad hoc network", Proc. of IEEE 56th VTC, V(4) , British Columbia, Canada, 2002, pp. 2435-2439.

[20] The VINT Project, "The ns manual", A Collaboration between researchers at UC Berkeley, LBL, USC/ISI, and Xerox PARC. , 2003.

[21] T. Nandagopal, T.E. Kim, X. Gao, V. Bharghavan, "Achieving MAC layer fairness in wireless packet networks". Proc. of 6th annual international conference on Mobile computing and networking, Boston, Massachusetts, United States, 2000, pp. 87-98.

[22] V. Bharghavan, A. Demers, S. Shenker, and L. Zhang, "MACAW: a media-access protocol for packet radio", Proc. of ACM SIGCOMM, 1994.

[23] X. Dong, M. Ergen, P. Varaiya, A. Puri, "Improving the aggregate throughput of access points in IEEE 802.11 Wireless LANs", Proc. of IEEE WLN, 2003.

[24] X. Yang, **"**A simple and effective priority scheme for IEEE 802.11", *Comm. Letters IEEE*, 7(2), 2003, pp. 70-72.

[25] Y. F. Wen, Frank Y.S. Lin, and K.W. Lai, "Access delay and throughput evaluation of block ACK under 802.11 WLAN", Proc. of 2nd IASTED CCN 2004, MIT, Cambridge, USA, Nov. 2004.

[26] Y. F. Wen, Frank Y.S. Lin, and K.W. Lai, "Maximization of system throughput subject to access time fairness constraints in multi-rate 802.11 WLANs",2nd ICT 2004, Bang Na Thailand, Nov. 2004, pp. 99-108.

Table 5. Experimental results

The parameters (the number of MHs (n_k), the number of multiple back-to-back packets (B_k), packet length (L_k), and initial contention windows (W_k)) for each bit rate.																System throughput (Mbps)	Holding time for each MH (μs)
1 Mbps				2 Mbps				5.5 Mbps				11 Mbps					
n_1	B_1	L_1	W_k	n_2	B_2	L_2	W_k	n_3	B_3	L_3	W_k	n_4	B_4	L_4	W_k		
1	1	2304	65									1	5	2286	31	4.156	16,289
1	1	2304	32	1	2	2245	31									1.330	20,225
								1	4	2304	48	1	5	2278	31	5.163	16,114
1	1	2259	65	1	1	2304	35	1	1	2268	70	1	5	2243	31	3.576	16,003
1	1	2304	61	1	4	2304	117					10	11	2301	60	5.626	15,495
10	1	2304	112	1	1	2304	58	1	3	2295	62	1	3	2291	33	1.860	15,855
10	1	2304	256	10	1	2300	80	1	1	2301	32	1	11	2293	153	1.800	12,903
10	1	2302	157	10	1	2304	81	10	8	2297	223	1	2	2294	32	2.505	16,569
10	1	2269	66	10	1	2304	35	10	6	2273	71	10	5	2250	31	3.544	16,181
1	1	2304	228	1	1	2304	117	1	3	2304	126	30	5	2298	105	5.923	14,621
1	1	2304	610	1	1	2304	310	30	2	2304	226	30	4	2304	225	5.068	10,629
1	1	2295	69	30	1	2304	36	30	6	2290	74	30	5	2263	32	4.145	15,718
30	1	2295	69	30	1	2304	36	30	5	2286	62	30	5	2263	32	3.499	15,971