An Adaptive Window Scheme for Backoff in 802.11 MAC Protocol

Priyesh Yadav Shetty
Department of Electrical Engineering
Indian Institute of Technology
Powai, Mumbai 400076, India.
110070006@iitb.ac.in

Vivek S. Borkar
Department of Electrical Engineering
Indian Institute of Technology
Powai, Mumbai 400076, India.
borkar.vs@gmail.com

Gaurav S. Kasbekar
Department of Electrical Engineering
Indian Institute of Technology
Powai, Mumbai 400076, India.
gskasbekar@ee.iitb.ac.in

ABSTRACT
We propose an extremely simple window adaptation scheme for backoff in 802.11 MAC protocol. The scheme uses constant stepsize stochastic approximation to adjust collision probabilities to set values, using an approximate analytic relationship between this probability and the back-off window. A further variation of this scheme also adapts the set points. Simulations show that our schemes, particularly the latter, ensure very good throughput and fairness.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless Communication*

General Terms
Theory, Performance

Keywords
802.11 MAC Protocol, Adaptive Backoff Window, Stochastic Approximation, Competitive Dynamics

1. INTRODUCTION
The Medium Access Control (MAC) protocol in 802.11 wireless networks, known as the Distributed Coordination Function (DCF), is a Carrier Sense Multiple Access/ Collision Avoidance (CSMA/ CA) based scheme that employs a binary exponential backoff algorithm [2]. Adaptive backoff window as a mechanism for its performance enhancement has been widely explored [3, 5, 6, 9, 11, 12]. In this article we propose an extremely simple scheme for backoff window adaptation that shows excellent performance in simulations. The idea is to use an approximate analytical relationship between window and collision probability arising out of 'fixed point analysis' [8] to write a stochastic approximation scheme that adjusts the transmission probability, interpreted in a 'frequentist' sense, towards a set value. In turn, we can also adapt the set value with an eye on QoS. Our scheme is distributed, can be independently executed by different nodes, and does not require message exchanges between nodes.

A methodological highlight is that instead of seeking a stationary scheme to modulate transmission probabilities as in [1], we modulate the relative frequency with a non-stationary scheme. This leads to time sharing by cycling though several possibilities in the decision space. In [3, 5, 6, 9, 11], the performance is evaluated only for a single hop network, *i.e.*, all nodes are in transmission range of each other. In contrast, we evaluate our scheme for a multi-hop network, in which only a subset of the nodes is in the transmission range of a given node. Secondly, in [3, 5, 9, 11], the scheme improves average throughput, but fairness is not evaluated. In our simulations, we consider homogeneous as well as heterogeneous deployments of nodes in a large region and in each case show that our scheme significantly outperforms the 802.11 MAC protocol in terms of average throughput *and* results in a fairer distribution of the throughput. Finally, our scheme is simpler to implement than those in [3] and [5], which require a packet sniffer in each node to monitor the transmission activities of all neighboring nodes. In our scheme, a node only needs to keep track of the fraction of *its own* transmission attempts that experienced a collision; so there is no need for a packet sniffer.

2. BACKGROUND
Recall the operation of the 802.11 MAC protocol [2]: when a node has a packet for transmission, it first senses the channel. If it is found to be idle for a short interval of time (the Distributed Inter-Frame Space (DIFS) [2]), the node starts transmitting the packet. Otherwise it selects a random backoff value K uniformly from the range $\{0, 1, \ldots, CW - 1\}$, where CW is the "Contention Window" [2]. It starts transmitting after the channel has been idle for K time slots, where the duration of a slot is a constant, say t_s. If there is no acknowledgment, e.g., in case a collision, it selects a random backoff value uniformly from a larger range than before and repeats the above process. Specifically, CW is set to a parameter CW_{min} for the first attempted transmission of a packet and doubled each time a collision occurs until the packet has experienced m consecutive collisions, after which it remains fixed at $CW = 2^m CW_{min}$. Typical values for the above parameters are $CW_{min} = 32$, $m = 5$, $t_s = 20\mu s$ and $DIFS = 50\mu s$. In [2], [8], the throughput of an IEEE 802.11 network was analyzed for the case when each node always has a packet to transmit. The analysis uses the following approximation: each transmission attempt of a node collides with a constant probability, say θ, independently of

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other attempts [2]. Let $\alpha :=$ the probability that a given node transmits a packet in a randomly chosen slot. Then in steady state (see Remarks 3.1, (2) in [8]):

$$\alpha = \frac{2(1-2\theta)}{(1-2\theta)(CW_{min}-1)+\theta CW_{min}(1-(2\theta)^m)}. \quad (1)$$

It was shown via simulations in [3] that the throughput performance of an 802.11 network strongly depends on the choice of the parameter CW_{min}. For a fixed CW_{min} (and m), the throughput significantly decreases as the number of contending nodes increases [3]. Thus, adapting the value of CW_{min} can substantially enhance the throughput performance of the network. In Section 3, we provide a distributed scheme that adapts the value of CW_{min} at each node based on the number of collisions its packets undergo.

3. THE ADAPTIVE SCHEME

Consider a network of nodes, each of which always has a packet to transmit. Two nodes are "neighbors" if they are in the transmission range of each other. Let $deg(i) :=$ the degree of node i. In each slot $n = 1, 2, \cdots$, node i uses the 802.11 MAC protocol except that it updates CW_{min} in each slot using the adaptive scheme described below.

Let $\alpha_i(n) :=$ the estimate of transmission probability for node i in slot n and $w_i(n) :=$ its initial contention window, CW_{min}, to be used in slot n. These are updated as follows:

$$\alpha_i(n+1) = \Gamma(\alpha_i(n) + a\chi_i(n)(\theta_i - I_i(n))), \quad (2)$$

$$w_i(n) = \frac{(\alpha_i(n)+2)(1-2\theta_i)}{\alpha_i(n)[1-2\theta_i+\theta_i(1-(2\theta_i)^m)]}, \quad (3)$$

where step size $a = 0.1$ and,

a) $\chi_i(n) := 1$ if node i attempts transmission, 0 otherwise,

b) $I_i(n) := 1$ if node i's packet experiences a collision, 0 otherwise,

c) $\theta_i :=$ the target value for the collision probability,

d) $\Gamma(\cdot)$ is the projection to the interval $[\epsilon, 1-\epsilon]$ for a small $\epsilon \in (0, 1)$, to ensure that the minimum and maximum values taken by $\alpha_i(n)$'s are $\epsilon, 1-\epsilon$, resp. (A typical $\epsilon = 0.1$).

This scheme is distributed and does not require message exchanges between nodes. The expression (3) is from (1), except that we now allow for a node-dependent choice of θ.

The algorithm (2) adjusts the estimate downwards if a collision occurs and upwards if it does not. Since this iteration is incremental, it sees the non-stationary environment as quasi-stationary and tracks the current collision probability, gradually adjusting it towards the set value θ_i. Let $h_i(\alpha)$ for $\alpha := [\alpha_1, \cdots]^T$ denote the collision probability for node i when $\alpha_i(t) \equiv \alpha_i\ \forall i, t$. By the theory of constant stepsize stochastic approximation algorithms ([4], Ch. 9), the algorithm will track within an error of order $O(a)$ the asymptotic behavior of the o.d.e.

$$\dot{\alpha}(t) = \theta_i - h_i(\alpha(t))\ \forall i, \quad (4)$$

with a componentwise projection to the boundary of $[\epsilon, 1-\epsilon]$. Since increasing α_i by node i (i.e., decreasing its contention window) will increase collision probabilities for the neighboring nodes, we expect $\frac{\partial h_j}{\partial \alpha_i}(\alpha) > 0$ when i, j are neighbors and ≥ 0 otherwise. This makes (4) a *competitive system* which can have a large variety of asymptotic behaviors [13]. The dynamics suggest that the collision frequencies hover around prescribed θ_i's so that the relative frequencies of collisions match the prescribed θ_i's asymptotically. We consider the following scenarios:

1) Fixed θ_i's: $\theta_i \propto deg(i), deg(i)^2, \sqrt{deg(i)}, \log_2(deg(i)+1)$, or constant θ_i.

2) Adaptive θ_i's: Here for $\theta_i(n) :=$ the value of θ_i in slot n and $thr_i(n) :=$ the successful fraction of node i's transmissions up to slot n, do:

$$\theta_i(n) = 0.1(1 - thr_i(n)). \quad (5)$$

4. SIMULATIONS

In this section, using simulations, we compare the network performance under the adaptive scheme with that under the non-adaptive 802.11 MAC protocol. We also study the evolution in time of the contention windows of nodes and other parameters under the adaptive scheme.

We consider a network of M nodes, and evaluate the performance of both schemes using (a) average throughput, $\frac{x_1+\ldots+x_M}{M}$, of the M nodes, where $x_j :=$ the throughput of the j'th node, and (b) *Jain's fairness index* (JFI) [7] given by:

$$\beta = \frac{(\sum_{j=1}^M x_j)^2}{(M \sum_{j=1}^M x_j^2)}.$$

β lies in $[0, 1]$ [7]. It increases with the degree of fairness of the distribution of throughput. In particular, if all nodes get equal throughput, $\beta = 1$, and if M' of the M nodes get equal throughput with the remaining $M - M'$ getting 0 throughput, $\beta = \frac{M'}{M}$ [7].

First we consider a homogeneous node deployment in which the location of each of the M nodes is independently selected uniformly at random in a square of dimensions 10 units $\times$ 10 units. Two nodes are neighbors iff the distance between them is less than d units, where $d = 6$ has been used throughout the simulations. We simulated the adaptive algorithm for the cases of both fixed and adaptive θ_i's (see the last para. of Section 3). Table 1 shows the average throughput and JFI for (i) all five versions of the adaptive algorithm with fixed θ_i's mentioned above, and for (ii) the adaptive algorithm with adaptive θ_i's for $M = 15$ and for $M = 50$ nodes. The second and third columns of the table show that for $M = 15, 50$, the adaptive algorithm with adaptive θ_i's significantly outperforms all versions of the adaptive algorithm with fixed θ_i's. The last two columns show that the JFI achieved by the schemes with $\theta_i = 0.01deg(i)$, $\theta_i = k(deg(i))^2$ and $\theta_i = 0.05\sqrt{deg(i)}$ are comparable to the JFI achieved by the adaptive scheme with adaptive θ_i's, whereas the JFI under the remaining two versions of the adaptive algorithm with fixed θ_i's are much lower. Overall, Table 1 shows that the adaptive algorithm with adaptive θ_i's performs much better than the algorithm with fixed θ_i's.

Next we compare the performance of the adaptive scheme

Table 1: Av. throughput and JFI for the adaptive algorithm. (For the scheme with $\theta_i = k(deg(i))^2$, for $M = 15$ (resp., $M = 50$), $k = 0.001$ (resp., $k = 0.0001$).)

Scheme	Average Throughput		JFI	
	$M = 15$	$M = 50$	$M = 15$	$M = 50$
$\theta_i = 0.1$	0.058	0.019	0.281	0.521
$\theta_i = 0.01deg(i)$	0.032	0.012	0.526	0.763
$\theta_i = k(deg(i))^2$	0.030	0.011	0.520	0.760
$\theta_i = 0.05\sqrt{deg(i)}$	0.028	0.009	0.519	0.754
$\theta_i = 0.05\log_2(deg(i)+1)$	0.049	0.016	0.223	0.447
Adaptive θ_i	0.105	0.030	0.521	0.761

with adaptive θ_i's (see (5)) with the 802.11 MAC protocol (non-adaptive scheme). Fig. 1 (respectively, Fig. 2) plots the average throughput (respectively, JFI) of the adaptive scheme, for two values of the parameter ϵ (see the para. after (3)), and of the non-adaptive scheme, versus the number of nodes M. It can be seen from Fig. 1 that for all values of M, the adaptive scheme achieves a significant improvement in average throughput over the non-adaptive scheme, with the average improvement being approximately 42% for both values of ϵ. Also, as expected, for each scheme the average throughput decreases in M since the number of collisions increases. Fig. 2 shows that for all values of M, the adaptive scheme with $\epsilon = 0.01$ achieves a significant improvement in JFI over the non-adaptive scheme, with the average improvement being approximately 11%. The figure also shows that better fairness is achieved with $\epsilon = 0.01$ than with $\epsilon = 0.001$ under the adaptive scheme. This is because the attempt probability, $\alpha_i(n)$, of every node i is constrained to lie in the range $[\epsilon, 1-\epsilon]$ (see the para. after (3)), which shrinks as ϵ increases.

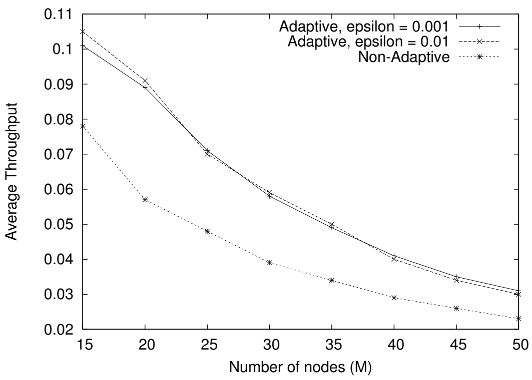

Figure 1: Av. throughput (homogeneous case).

We then consider a heterogeneous node deployment which differs from the homogeneous case considered above in the following respect: the square in which the M nodes are located is now divided into four equal squares s_1, s_2, s_3 and s_4 and the location of each node is uniformly distributed in square s_i with probability p_i for $i \in \{1, 2, 3, 4\}$, independently of the other nodes. The values $p_1 = p_3 = 0.35$, $p_2 = p_4 = 0.15$ have been used throughout the following simulations. Figs. 3 and 4 show the average throughput and JFI respectively for the heterogeneous scenario versus the number of nodes. It can be seen that the trends in these figures are similar to those in Figs. 1 and 2. In particular, on average, the improvement in average throughput (resp., JFI) achieved by the adaptive scheme with $\epsilon = 0.001$ (resp.,

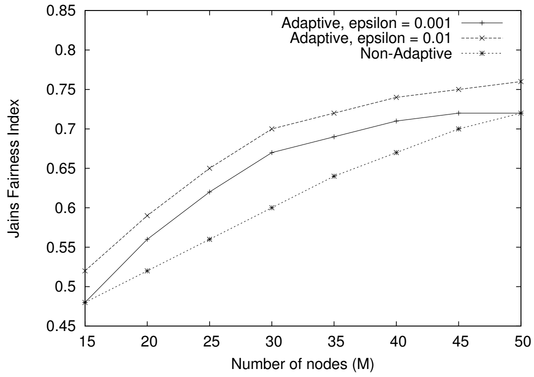

Figure 2: JFI (homogeneous case).

$\epsilon = 0.01$) over the non-adaptive scheme is approximately 17.8% (resp., 18.5%).

In summary, the adaptive scheme achieves a significant improvement in terms of average throughput as well as fairness over the non-adaptive scheme for networks of various sizes (*i.e.*, number of nodes) and node deployment schemes (homogeneous / heterogeneous).

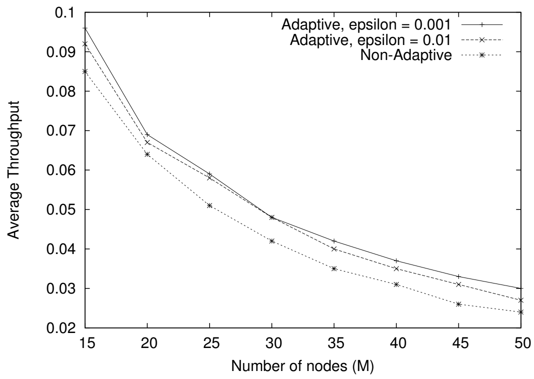

Figure 3: Av. throughput (heterogeneous case).

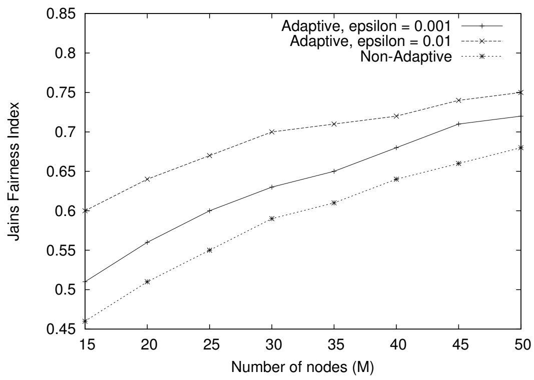

Figure 4: JFI (heterogeneous case).

We also study the time evolution of the adaptive scheme dynamics in (2) and (3) with adaptive θ_i's (see (5)) via simulations. Consider a network of $M = 50$ nodes deployed homogeneously. Fig. 5 plots $\theta_i(n)$ as in (5) vs n for the nodes with maximum and minimum degrees ($deg(i)$) and for a node with degree close to the average degree, in a time window after the system has reached steady-state. The figure shows that for each i, $\theta_i(n) :=$ the fraction of node i's transmissions that experience a collision up to time n converges to a constant value. Moreover, the higher the degree of the node, the larger is this constant, which is consistent with the intuition that as the number of neighbors of a node increases, so does the likelihood of a collision. Fig. 6 (resp., Fig. 7) plots $\alpha_i(n)$ (resp., $w_i(n)$) vs n for these three nodes. The figures show that $\alpha_i(n)$, and hence $w_i(n)$ (note that $w_i(n)$ decreases as $\alpha_i(n)$ increases by (3)), oscillates with time for each node i in steady-state. Such oscillatory behavior is common in competitive systems, of which the system in (2) and (3) is an instance (see the para. after (4)). The figures also show that for much of the time, nodes i with a high degree, $deg(i)$, have a low $\alpha_i(n)$, and correspondingly a high $w_i(n)$, which is because the likelihood of a collision increases in $deg(i)$ and the algorithm (2) adjusts the estimate downwards if a collision occurs and upwards if it does not.

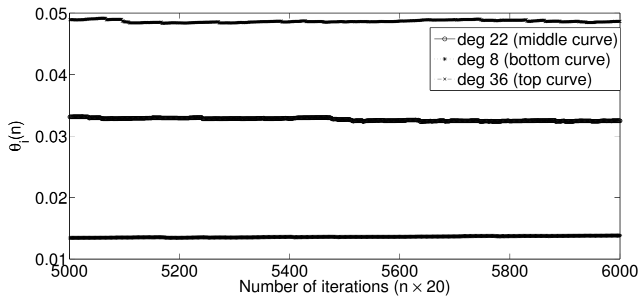

Figure 5: Steady state $\theta_i(n)$ vs n for nodes with maximum / minimum degrees and for a node with degree close to the average degree.

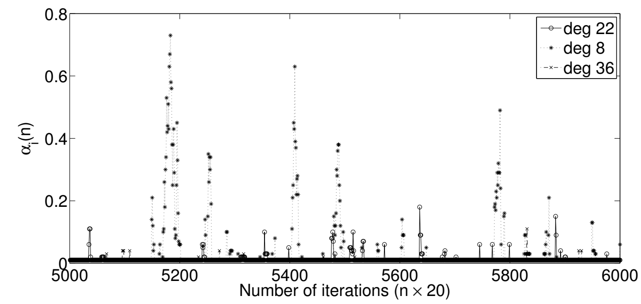

Figure 6: Steady state $\alpha_i(n)$ vs n for nodes with maximum / minimum degrees and for a node with degree close to the average degree.

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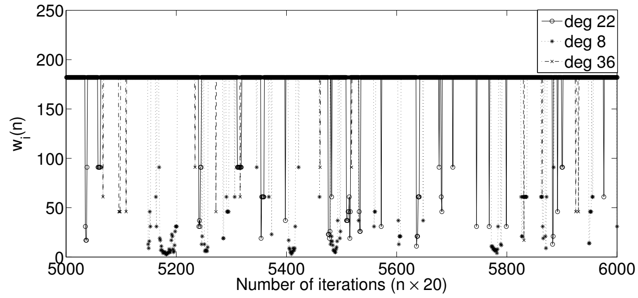

Figure 7: Steady state $w_i(n)$ vs n for nodes with maximum and minimum degrees and for a node with degree close to the average degree.

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