Collision-aware Design of Rate Adaptation for Multi-rate 802.11 WLANs

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Abstract

One of the key challenges in designing a rate adaptation scheme for IEEE 802.11 wireless LANs (WLANs) is to differentiate bit errors from link-layer collisions. Many recent rate adaptation schemes adopt the RTS/CTS mechanism to prevent collision losses from triggering unnecessary rate decrease. However, the RTS/CTS handshake incurs significant overhead and is rarely activated in today's infrastructure WLANs. In this paper we propose a new rate adaptation scheme that mitigates the collision effect on the operation of rate adaptation. In contrast to previous approaches adopting fixed rate-increasing and decreasing thresholds, our scheme varies threshold values based on the measured network status. Using the "retry" information in 802.11 MAC headers as feedback, we enable the transmitter to gauge current network state. The proposed rate adaptation scheme does not require additional probing overhead incurred by RTS/CTS exchanges and can be easily deployed without changes in firmware. We demonstrate the effectiveness of our solution by comparing with existing approaches through extensive simulations.

Index Terms

Rate Adaptation, 802.11, Adaptive threshold

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I. Introduction

Rate adaptation has become one of the basic functionalities in today's 802.11 WLANs. It is designed to cope with the variation of wireless channels and achieve higher system spectral efficiency by exploiting the multi-rate capability provided by the IEEE 802.11 physical layer (PHY). The current 802.11 PHY [1] supports a wide range of transmission rates between 1 and 54 Mbps by employing different sets of modulation and channel coding schemes. For example, IEEE 802.11b supports four data rates 1, 2, 5.5, and 11 Mbps whereas 802.11a/g support eight up to 54 Mbps [1], [2]. The efficiency of rate adaptation has a significant effect on the system performance of WLANs. Nevertheless, the IEEE 802.11 standard does not specify a rate selection algorithm or protocol to exploit its multi-rate capacity, i.e. rate adaptation is left to vendor discretion.

The basic idea of rate selection is to estimate the channel condition and adaptively select the best rate out of multiple available transmission rates. Although the available transmission rates depend on the receiver's channel state, the 802.11 standard does not provide receiver's explicit feedback information about the best rate or perceived SNR to the transmitter except an Acknowledgement (ACK) after a successful reception of a data frame. Due to such limitation, most rate adaptation schemes [9], [23], [27], [29], [32] decide transmission rate at the transmitter, based only on its local information. In particular, the history of past ACK information is commonly used to decide future rates. For example, *automatic rate fallback* (ARF) [22], one of the most widely implemented rate adaptations, uses the transmission history to select its next transmission rate. In ARF, two consecutive transmission failures—i.e. ACK is not received—result in rate downshift to the next lower rate. After the reception of ten consecutive ACKs, the next higher rate is selected for the transmission of next data frame. Here, if the delivery of the eleventh frame is unsuccessful, ARF immediately falls back to the previously used transmission rate. Most practical rate adaptations implement variants of the canonical ARF based on up/down counter mechanism [3], [11], [23], [24], [27], [29] or otherwise use statistics of previous data deliveries based on the 802.11 ACK feedback mechanism [9], [32].

The performance and efficiency of rate adaptation depend on the rate control parameters such as up/down thresholds. For example, fast-fading channels require a small value of up-threshold in order to keep up with rapid channel variations [11]. Conversely, for slowly changing channels, the use of a large value of up-threshold can prevent excessive rate-increasing attempts. Several research efforts [11], [24], [29] have dealt with time-varying wireless channel characteristics through adaptive up/down-thresholds.

Unfortunately, most rate adaptations only focus on the time-varying characteristics of wireless channels and do not consider the impact of link-layer collisions. They assume that all transmission failures—inferred from missing 802.11 ACKs—are due to channel errors even though absence of an ACK is not always due to channel error, i.e., many transmission failures are due to link-layer collisions in multi-user contention-based 802.11 networks. As a result, they respond to frame collisions—which cannot be distinguished from channel errors based on missing 802.11 ACKs alone—resulting in unnecessary rate downshift (to be more robust to bit-errors) even when channel condition is not bad. This can significantly decrease throughput when transmission failures are caused by collisions [13], [15], [23].

To mitigate the collision effect, a number of recently proposed schemes [19], [23], [27], [32] leverage the per-frame RTS option and selectively turn on RTS/CTS exchange. The feedback information obtained from the RTS/CTS handshake can enable the transmitter to differentiate collisions (i.e., indicated by a failure of RTS frame) from channel errors (i.e., indicated by a unsuccessful data frame transmission following a successful RTS/CTS handshake). However, RTS/CTS is rarely turned on in practical infrastructure IEEE 802.11 WLANs due to high overhead. Per-frame selective RTS also remains a costly solution in lossy environments.

In this paper, we address the performance degradation problem of rate adaptation stemming from detrimental rate-down shift operations wrongly triggered by link-layer collisions. Our main objective is to find a solution that does not require additional probing overhead such as those incurred by RTS/CTS exchanges. Our key idea is that dynamic adjustment of up/down-thresholds can be useful not only to cope with channel dynamics [11], [29] but also to mitigate the impact of collisions. As the number of contending stations increases, the number of collisions is also likely to increase triggering unnecessary—in fact, detrimental—rate-downshifts. In such a situation, a higher value of down-threshold can reduce undesired rate-downshifts. Similarly, a smaller value of up-threshold can help recover from unintended rate-decreases induced by collisions.

Motivated by the above observation, we present a new approach that mitigates the collision effect on the operation of rate adaptation in IEEE 802.11 WLANs by adaptively adjusting the rate-increasing and decreasing parameters. Instead of distinguishing between channel errors and collisions based on costly RTS/CTS mechanism, we use a link-layer congestion metric that infers network congestion state gauged by local observations at the transmitter. We develop a novel congestion sensing technique by exploiting the 802.11 standard's retransmission mechanism, in particular, the *Retry* field in 802.11 MAC header which indicate whether a data or management frame is being transmitted for the first time or is a retransmission. Our key observation is that *the pattern of this Retry field can be used as channel feedback for inferring channel contention information* since it is influenced by collision events. The main advantage of this metric is that it can be easily measured by monitoring the retransmission state of frames being transmitted in a WLAN without extra overhead. The result is then used to control the operating thresholds adaptively so as to mitigate the collision effect on rate adaptation. The simulation results show that our new estimation scheme based on the link-layer retransmission information is efficient in gauging the channel state, and the adaptively tuned thresholds are effective not only at offsetting the collision effect but also improving the responsiveness to channel variation. Our solution does not require additional probing overhead and can be practically deployed without changes in firmware.

The remainder of the paper is organized as follows. In Section II, we formulate the problem and introduce the framework of our approach. Section III analyzes the impact of rate-control parameters on system performance. In Section IV, we study adaptive threshold tuning. In Section V, we present a new link-layer sensing technique that exploits the 802.11's retransmission protocol and propose a run-time algorithm to adaptively control the operating thresholds. The performance of our solution is evaluated via extensive simulation in Section VI. We conclude with a discussion of related work.

II. Problem Formulation

We consider a station adopting ARF in a multi-rate IEEE 802.11 WLAN. Let θ_u and θ_d denote the up and down thresholds of ARF, respectively, where θ_u consecutive successes trigger a rate upshift (more precisely, up-rate probing to the next higher rate [22] [13]) and θ_d consecutive transmission failures result in a rate downshift to the next lower rate. The canonical ARF uses fixed thresholds $\theta_u = 10$ and $\theta_d = 2$. Note that other variants of the canonical ARF may use different values or variable thresholds [11] [29]. For example, AARF [24] uses a binary exponential up-threshold θ_u while its down-threshold θ_d is fixed at 2. The thresholds used in these schemes do not consider the collision effect.

Our objective is to mitigate the unintended rate shift stemming from collisions. Instead of RTS/CTS, we aim to improve the operation of rate adaptation by adjusting its rate-control thresholds based on estimation of link-layer conditions. The goal of our approach is to find new thresholds (x_u, x_d) offsetting the collision effect experienced under original operation with (θ_u, θ_d). (x_u, x_d) is determined by current link-layer condition (i.e., collision probability) and the thresholds (θ_u, θ_d) of target rate adaptation schemes. Thus, we can state the problem as

$$x_u = f_u(\theta_u, p) \text{ and } x_d = f_d(\theta_d, p) \tag{1}$$

where p represents the current link-layer contention status, i.e., collision probability. Finding the threshold tuning functions $f_u(\cdot)$ and $f_d(\cdot)$ is the key problem.

The first challenge in deriving $f_u(\cdot)$ and $f_d(\cdot)$ is the lack of a *target reference point* for up/down-thresholds that indicates what rate adaptation behavior is optimal to mitigate the collision effect. This issue is addressed next.

III. Performance of ARF and Its Ideal Behavior

In this section we study the impact of up/down thresholds on ARF performance and show that dynamic adjustment of thresholds is an effective way to mitigate the collision effect. We use the ARF analysis model proposed in [13] to understand the rate-shifting behavior of ARF. We first review the ARF Markov chain model briefly.

A. Analytic Model of ARF

The analysis considers a station adopting ARF in a multi-rate IEEE 802.11 WLAN with L data rates $R_1 < R_2 < \cdots < R_L$ in units of Mbps, where the WLAN consists of N stations. For example, in 802.11b $L = 4$ with rates 1, 2, 5.5, and 11 Mbps. For each rate R_i and given a fixed frame size, the station is supposed to have a frame error rate (FER) e_i obeying $e_1 \leq e_2 \leq \cdots \leq e_L$ due to the increased robustness of 802.11 PHY modulation at lower data rates. Following Bianchi [7], we introduce the independence assumption that in equilibrium a frame transmission experiences collisions with constant and independent probability p. Thus the conditional transmission failure probability of a frame transmitted at rate R_i is given by $p_i = 1 - (1-p)(1-e_i)$. Note that even though the transmission failure probability p_i consists of p and e_i, ARF can not recognize p and e_i separately and it only behaves according to the aggregated value of p_i.

The key observation we can find in the ARF algorithm is that *the transmission rate is always switched to adjacent one*, so that the rate adaptation procedure of ARF could be expressed via *a birth-death Markov chain* as shown in Fig. 1, where the state i represents the transmission rate R_i of the single target station. Note that each state in this chain is a macro-state which contains micro-states representing the consecutive counters of ARF (the details are described in [13]).

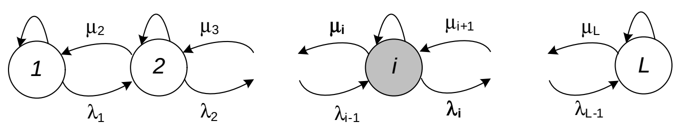


Fig. 1. Birth-death Markov Chain for ARF (L PHY rates)

Let Π_i denote the steady-state probability of the ARF chain that captures a station's probability of transmitting at data rate R_i. λ_i ($i \in \{1, 2, \ldots, L-1\}$) and μ_i ($i \in \{2, \ldots, L\}$) denote the state transition probabilities of increasing the current rate i to $i+1$ and decreasing the current rate i to $i-1$, respectively. The equilibrium distribution of a L-state discrete-time birth-death chain with birth probabilities λ_i and death probabilities μ_i is given by

$$\Pi_1 = \frac{1}{1 + \sum_{j=1}^{L-1} (\prod_{k=1}^{j} \frac{\lambda_k}{\mu_{k+1}})} \text{ and } \Pi_i = \frac{\lambda_{i-1}}{\mu_i} \Pi_{i-1}, \tag{2}$$

for $i \in \{2, \ldots, L\}$. In [13], we derived λ_i and μ_i for a stationary and independent p_i and two thresholds θ_u, θ_d which are as follows:

$$\begin{aligned} \lambda_i &= \frac{p_i (1-p_i)^{\theta_u}}{1 - (1-p_i)^{\theta_u}}, \\ \mu_i &= p_i^{\theta_d}, \end{aligned} \tag{3}$$

This means that when ARF is in a certain stationary channel condition with a transmission failure probability p_i, it increases current rate i to $i+1$ with the probability of λ_i and decreases current rate i to $i-1$ with the probability of μ_i. Eq. (3) also implies that *the rate-shifting probabilities can be controlled by adjusting thresholds* θ_u *and* θ_d. It is of practical importance to understand the behavior of ARF and improve its performance.

B. Impact of Thresholds on ARF Performance

Using the ARF analysis model, we now characterize the impact of both link-layer contention and up/down thresholds on ARF performance. Fig. 2 shows ARF-DCF throughput in 802.11b PHY environment for different combinations of the up/down thresholds as the number of contending station N is varied. We consider a stationary (i.e., no fading) channel state of SINR=9dB at which $\text{BER}_{\text{11Mbps}} = 10^{-3}$, where we use empirical BER versus SNR curves provided by Intersil [4]. All stations use equal up/down thresholds.

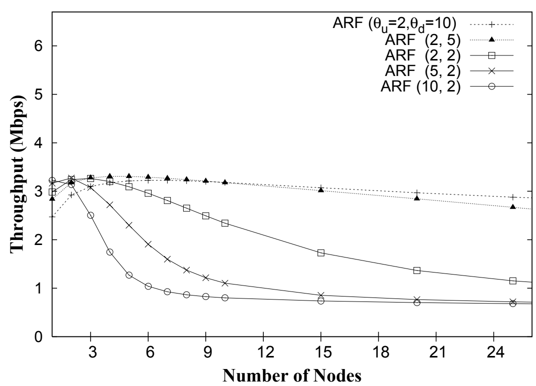


Fig. 2. ARF-DCF throughput for various θ_u and θ_d combinations at SINR=9dB (1000 bytes)

We observe that the performance of ARF is significantly influenced by both current link-layer contention state and up/down-thresholds. When the number of stations N is small (N=1 or 2), the default value θ_u=10 and θ_d=2 used in canonical-ARF achieves reasonable performance. However, its performance drops precipitously as the number of contending station N increases. The steep decline in throughput is caused by ARF's inability to effectively differentiate channel noise from collision. With $\theta_u = 2$ and $\theta_d = 10$, thanks to its large value of down-threshold, ARF avoids the detrimental rate-down shift due to collisions and achieves high performance even at the high contention region (i.e., large N). However, since the large threshold value is apt to slow down responsiveness of rate selection, it can be harmful in fast-fading channel environments [11], [29]. The results imply that dynamic tuning of thresholds may be effective at mitigating the collision effect but excessive tuning may hurt the ARF's innate responsiveness to channel variation. Thus, tuning should be done adaptively depending on network condition.

C. Ideal Behavior of ARF

As discussed in the previous section, it is well-known that when a WLAN has a number of active stations, It is known that in a WLAN with moderate multiple access contention ARF may lose its effectiveness due to the detrimental rate down-shift wrongly triggered by collisions [15]. To remedy this problem, *ARF should not react to collisions but respond only to channel errors,* i.e., frame losses due to collisions should be filtered out from ARF's failure counting.

Let us consider the ideal case where a station has perfect knowledge of the cause of transmission failures without additional probing overhead such as RTS/CTS exchange. Its rate adaptation can perfectly prevent missteps due to collisions, and hence attain its maximum achievable throughput. We refer to such ARF having perfect collision filtering ability as *ideal ARF* (or *Ideal Collision Filtering ARF*). Even though *ideal ARF* is not realizable, we can analytically characterize its behavior using our ARF Markov chain model.

Let $\Pi_i^{opt}(\theta_u, \theta_d)$ denote the probability of transmitting at rate R_i of *ideal ARF* with originally configured up/down-thresholds θ_u and θ_d. As *ideal ARF* reacts only to channel errors, its response probability to frame errors is not p_i but $(1-p)e_i$ ($= p_i - p$). Therefore, its transition probabilities $\lambda_i^{opt}, \mu_i^{opt}$ at R_i are given by

$$\begin{aligned} \lambda_i^{opt} &= \frac{(1-p)e_i\{1-(1-p)e_i\}^{\theta_u}}{1-\{1-(1-p)e_i\}^{\theta_u}}, \\ \mu_i^{opt} &= \{(1-p)e_i\}^{\theta_d} \end{aligned} \tag{4}$$

which are obtained by substituting ($p_i - p$) for p_i into Eq. (3). Similarly, we can obtain the probabilities $\Pi_i^{opt}(\theta_u, \theta_d)$ ($i \in \{1, \ldots, L\}$) using Eq. (2). In Fig. 3, we compare the throughput of ARF and *ideal ARF* for θ_u=10 and θ_d=2 as an example (same channel condition as Fig. 2).

Eqs. (4) characterize the optimal behavior of ARF that alleviates the collision effect. We use λ_i^{opt} and μ_i^{opt} as the *target reference value* to control up/down-thresholds in our algorithm.

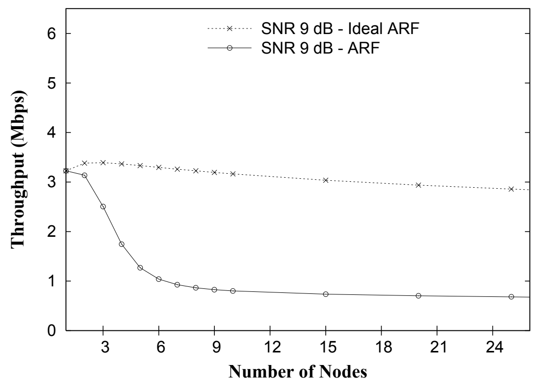


Fig. 3. Performance of *ideal ARF* (θ_u=10, θ_d=2) at SINR=9dB (1000 bytes)

IV. Collision-aware Threshold Tuning

Our objective in this section is to find new collision-robust thresholds (x_u, x_d) in place of the original thresholds (θ_u, θ_d) that offset the collision effect experienced when working with (θ_u, θ_d).

A. Basic Idea

When ARF with thresholds (θ_u,θ_d) experiences stationary and independent transmission failure probability p_i (following [7]), its rate-shifting probabilities λ_i, μ_i are calculated as in Eq. (3) while its ideal behavior follows λ_i^{opt}, μ_i^{opt} in Eqs. (4). The difference between these probabilities, i.e., $\lambda_i^{opt} - \lambda_i$ and $\mu_i - \mu_i^{opt}$, can be regarded as the impact of collision on ARF's rate-shifting where $\lambda_i^{opt} - \lambda_i = 0$ and $\mu_i - \mu_i^{opt} = 0$ if $p = 0$.

As shown in Eq. (3), the rate-shifting probabilities λ_i, μ_i of ARF can be controlled by adjusting its thresholds. A change in λ_i, μ_i induces a change in $\lambda_i^{opt} - \lambda_i$ and $\mu_i - \mu_i^{opt}$ that quantify the collision effect. Thus, we select the up-threshold and down-threshold that minimize $\lambda_i^{opt} - \lambda_i$ and $\mu_i - \mu_i^{opt}$ as new up-threshold x_u and down-threshold x_d, respectively. To formulate our approach, let us denote the rate-shifting probabilities λ_i and μ_i in Eq. (3) as $\lambda_i(\theta_u, p_i)$ and $\mu_i(\theta_d, p_i)$. Similarly, we represent the ideal rate-shifting probabilities λ_i^{opt} and μ_i^{opt} in Eq. (4) as $\lambda_i^{opt}(\theta_u, p, e_i)$ and $\mu_i^{opt}(\theta_u, p, e_i)$. The collision mitigating thresholds x_u, x_d are obtained by solving

$$\begin{aligned} \lambda_i(x_u, p_i) &= \lambda_i^{opt}(\theta_u, p, e_i), \\ \mu_i(x_d, p_i) &= \mu_i^{opt}(\theta_d, p, e_i), \end{aligned} \tag{5}$$

which yield

$$\begin{aligned} x_u &= \frac{\ln \frac{\lambda_i}{\lambda_i + p_i}}{\ln(1-p_i)} = \frac{\ln \dfrac{(1-p)e_i(1-(1-p)e_i)^{\theta_u}}{p_i + p(1-(1-p)e_i)^{\theta_u}}}{\ln(1-p_i)}, \\ x_d &= \frac{\ln \mu_i}{\ln p_i} = \theta_d \frac{\ln (1-p)e_i}{\ln p_i}, \end{aligned} \tag{6}$$

where $p_i = 1 - (1-p)(1-e_i)$.

If we know the collision probability p and the frame error probability e_i, we can obtain the link-layer adaptive thresholds x_u, x_d using Eq. (6). This requires that stations estimate e_i for each rate ($i \in \{1, 2, \ldots, L-1\}$) and p separately. In practice, it is difficult to predict the instant channel error rate accurately without modification of the 802.11 standard. ARF neither estimates nor uses the transmission failure rate p_i, to say nothing of e_i. In our approach, we also avoid estimation of e_i. Instead, our scheme makes use of link-layer measurement as follows: even though stations in a 802.11 WLAN cannot differentiate collisions from channel errors given transmission failures, they can estimate the link-layer status (i.e., the collision probability p or the number of competing stations N) by using existing on-line measurement and estimation algorithms [8], [21], [25], [30]. In the next section, we discuss an estimation method for the collision probability p.

B. Adaptive Threshold Independent of Channel Condition

Let us express x_u, x_d in Eq. (6) as $x_u = f_u'(\theta_u, p, e_i)$, $x_d = f_d'(\theta_d, p, e_i)$. To design an algorithm that does not require channel information such as Eq. (1), we need to remove the input term e_i in $f_u'(\theta_u, p, e_i)$ and $f_d'(\theta_d, p, e_i)$. For a given collision probability p, the adaptive thresholds x_u, x_d have different values according to channel error e_i. Fig. 4 plots the $f_u'(\theta_u, p, e_i)$ function for several values of collision probability p with respect to all e_i ($0 < e_i \leq 1$), i.e., $p < p_i \leq 1$, where the rate-increasing threshold θ_u is set to 10. From Fig. 4, we can see that the range of $f_u'(\cdot)$ (i.e., x_u) for various e_i is not large except when e_i is large ($p_i \approx 1$). A notable observation is that *the conservative nature of rate adaptations keeps the channel condition at the low noise*

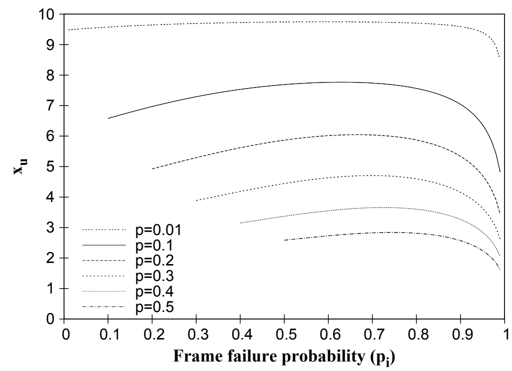


Fig. 4. $x_u = f'_u(\theta_u, p_i)$ for arbitrary channel condition ($p < p_i \leq 1$) for θ_u = 10

regime (i.e., rate adaptations select a transmission rate at which the channel noise is low). We can thus ignore the high noise region (large e_i) in Fig. 4. Since the range of x_u for the effective range of e_i becomes narrow, we use an integer closest to x_u for $p < p_i \ll 1$ as the final value of $f'_u(\cdot)$. To simplify the algorithm and avoid excessive control, we use a conservative heuristic that sets $x_u = \max\{f_u(\theta_u, p, e_i)\}$ for e_i ($0 < e_i \leq 1$). For example, we have chosen $x_u = 4.7$ for $p = 0.3$ in Fig. 4. Similarly, we set $x_d = \min\{f_d(\theta_d, p, e_i)\}$ for e_i ($0 < e_i \leq 1$). Note that the smaller value of x_u and larger value of x_d imply more aggressive control.

We obtain the control function in Eq. (1) for thresholds (θ_u, θ_d) as follows:

$$x_u = f_u(\theta_u, p) = \max_{p<p_i\leq 1}\left\{\frac{\ln\dfrac{(p_i-p)(1-(p_i-p))^{\theta_u}}{p_i+p(1-(p_i-p))^{\theta_u}}}{\ln(1-p_i)}\right\},$$
$$x_d = f_d(\theta_d, p) = \min_{p<p_i\leq 1}\left\{\theta_d \cdot \frac{\ln(p_i-p)}{\ln p_i}\right\}. \tag{7}$$

For example, we show the link-layer adaptive thresholds x_u, x_d for ARF (θ_u=10, θ_d=2) with respect to the number of contending stations N and resultant collision probability p [7] in Table I. Consider the case $N = 5$ whose collision probability is $p = 0.181$. For ARF working with default thresholds θ_u=10 and θ_d=2, its adaptive thresholds are x_u = f_u(10, 5) = 6.34 and x_d = f_d(2, 5) = 3.29. Since thresholds should be integers, we round $[x_d] = 6$, $[x_u] = 3$. Fig. 5 compares throughput (analytical result) under $N = 5(p \approx 0.18)$ for different combinations of up/down thresholds over a wide range of channel conditions. Fig. 5 shows that for $N = 5(p = 0.18)$, our adaptive method (x_u=6, x_d=3) offsets the collision effect experienced under (θ_u=10, θ_d=2).

TABLE I

VALUES OF (x_u, x_d) FOR ARF (θ_u=10, θ_d=2)

N	p	x_u	x_d	N	p	x_u	x_d
1	0	10	2	11	0.308	4.61	4.74
2	0.059	8.62	2.35	12	0.322	4.45	4.94
3	0.107	7.63	2.68	13	0.335	4.31	5.14
4	0.147	6.90	2.99	14	0.346	4.19	5.32
5	0.181	6.34	3.29	15	0.357	4.08	5.50
6	0.210	5.90	3.57	20	0.402	3.64	6.33
7	0.235	5.54	3.83	25	0.436	3.34	7.08
8	0.256	5.25	4.07	30	0.463	3.12	7.75
9	0.276	5.00	4.31	40	0.507	2.79	9.03
10	0.293	4.79	4.53	50	0.540	2.57	10.19

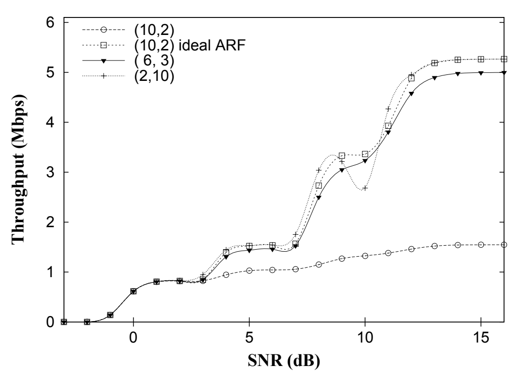


Fig. 5. ARF-DCF throughput for various θ_u, θ_d combinations under $N = 5$

We also compare our result with more aggressive control (x_u=2, x_d=10). The collision effect is almost mitigated with (x_u=2, x_d=10) due to its large down-threshold value but it does not work properly for a range of channel errors near 10dB.

We need a control algorithm to estimate the link-layer collision probability p (or number of contending station N) and make thresholds x_u, x_d converge to their target values. In the next section, we discuss link-layer estimation and propose a run-time control algorithm.

V. A New Congestion Sensing Technique and Run-time Adaptation Algorithm

A. 802.11 Feedback for Inferring Network Status

In a WLAN, all contending stations experience a same collision probability while they have different channel error probabilities. The collision probability p is a common shared variable of all contending stations and can be measured by each individual station via monitoring the channel state [8], [12], [14], [18], [21]. In particular, the number of idle slots between two consecutive busy periods can be used to estimate the number of contending stations and collision probability.

We propose a new technique to estimate the number of active stations N (and collision probability p) using the frequency of retransmitting frames in 802.11 WLANs. Fig. 6 shows the

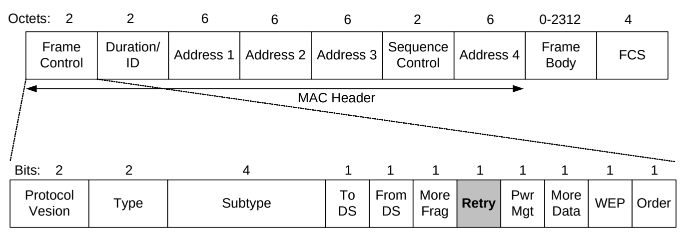


Fig. 6. General IEEE 802.11 MAC layer frame format

format of a general IEEE 802.11 MAC layer frame. The *Retry* field in the 802.11 MAC header is a single bit and is used to indicate whether a data or management frame is being transmitted for the first time or is a retransmission (0 or 1). The receiving MAC uses this indication to aid in the process of eliminating duplicate frames. A key observation is that *the retry field can be used as channel feedback for inferring the channel condition* because there is correlation between collision probability and the pattern of retry values in arriving frames. As the channel becomes more congested, the number of retransmissions is also likely to increase. When a station detects frame transmission, it checks if the received frame is intended for itself by looking at the receiver address field in MAC header. At this step, each station can inspect the value of Retry field included in the MAC header. By exploiting the Retry field pattern, we can quantify the degree of contention in the channel.

B. A Novel Congestion Sensing Technique

In order to model and analyze the pattern of Retry field, we reuse Bianchi's Markov chain model [7]. Fig. 7 shows a discrete-time Markov chain model that describes the backoff window scheme of 802.11 DCF. Following [7], let $b(t)$ and $s(t)$ be the stochastic process representing

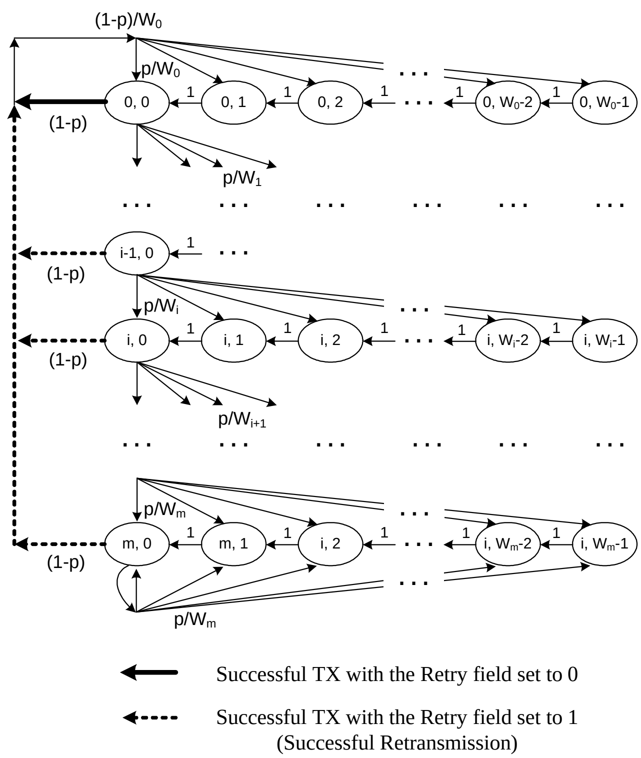


Fig. 7. Markov Chain Model for the 802.11 DCF's exponential backoff procedure proposed in [7]

the backoff window size for a given station and the stochastic process representing the backoff stage $(0, ..., m)$ of a station at time t, respectively, where m represents the maximum backoff stage. The two-dimensional process $\{s(t), b(t)\}$ is represented by state $\{s(t) = i, b(t) = k\}$ at time t. The stationary distribution of the chain is denoted by $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\}$, $i \in (0, m), k \in (0, W_i - 1)$, where $W_i = 2^i CW_{min}$.

We describe the Retry field pattern using the Markov chain in Fig. 7. A transmission occurs when the backoff time counter is equal to zero, hence a transition from states $\{i,\ 0\}$ ($i \in (0, m)$) in the chain represents a frame transmission. The Retry field is set to 0 for the transmission from the backoff stage 0, i.e., state $\{0,\ 0\}$, and set to 1 at other stages, i.e., states $\{k,\ 0\}$, $k \in (1, m)$.

Upon successful reception of a frame, each station counts the frequencies of frames with the retry field $= 0$ and 1. Let C_j ($j = 0, 1$) denote the numbers of frames whose Retry field is j. We calculate the probability of successful transmissions at the first attempt as follows:

$$\frac{C_0}{C_0 + C_1} = \frac{(1-p)b_{0,0}}{(1-p)b_{0,0} + (1-p)\sum_{k=1}^{m} b_{k,0}}. \tag{8}$$

Using the relation $b_{i,0} = p^i b_{0,0}$ [7], we obtain

$$\frac{C_0}{C_0 + C_1} = \frac{(1-p)b_{0,0}}{(1-p)\sum_{k=0}^{m} b_{k,0}} = \frac{1-p}{1-p^m} \tag{9}$$

which yields

$$p^m + p^{m-1} + \ldots + p - \frac{C_1}{C_0} = 0. \tag{10}$$

With the measured value of C_1/C_0, we can calculate the collision probability p from Eq. (10). Table II shows the relation between the number of contending stations N (and collision probability p) and C_1/C_0 when the 802.11's LongRetryLimit is 4 (i.e. m=4).

TABLE II

NUMBER OF CONTENDING STATIONS N, COLLISION PROBABILITY p AND CORRESPONDING C_1/C_0 (RETRYLIMIT = 4)

N	p	C_1/C_0	N	p	C_1/C_0
1	0.000	0.000	11	0.308	0.441
2	0.059	0.062	12	0.322	0.470
3	0.107	0.120	13	0.335	0.497
4	0.147	0.173	14	0.346	0.522
5	0.181	0.221	15	0.357	0.547
6	0.210	0.265	20	0.402	0.654
7	0.235	0.306	25	0.436	0.745
8	0.256	0.343	30	0.463	0.824
9	0.276	0.378	40	0.507	0.960
10	0.293	0.411	50	0.540	1.075

Note that retransmissions are induced not only by collisions but also channel errors. Therefore, we have to consider the impact of channel errors. We first verify that C_1/C_0 is a reliable reference even in the presence of channel errors.

1) Impact of Channel Errors on Retry Field: To be a useful reference that reflects link-layer contention, C_1/C_0 must be a one-to-one mapping with respect to N for each fixed channel error probability. Fig. 8 shows C_1/C_0 as a function of N for various channel error probabilities. We observe that C_1/C_0 increases as N increases. At a given channel error probability, we can uniquely estimate N from measured C_1/C_0. A problem is that in the real world we cannot determine N from C_1/C_0 since the channel error probability is unknown.

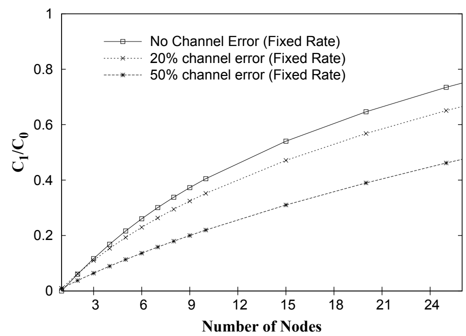


Fig. 8. The impact of channel errors on C_1/C_0 with respect to the number of contending stations (homogeneous environment)

2) ARF's Regulation Effect on Channel Error: ARF is designed to react to frame losses quickly and selects a conservative data rate such that the transmission error probability is low. This implies that ARF maintains the channel condition in the low noise regime. Fig. 9 shows the impact of ARF on the relation between C_1/C_0 and N for various channel conditions. Unlike Fig. 8, it shows that C_1/C_0 is a good reference for the estimation of N regardless of channel state (SNR) due to ARF's conservative rate selection property.

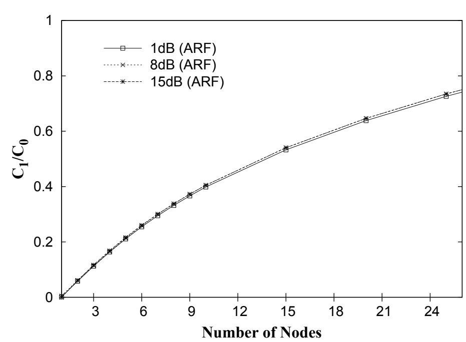


Fig. 9. The impact of conservative nature of ARF on the relation between N and C_1/C_0 in various channel environments

TABLE III

THRESHOLD TABLE FOR E[C_1/C_0] (θ_u=10, θ_d=2) : $x_u = f_u$(10, E[C_1/C_0]), $x_d = f_d$(2, E[C_1/C_0]), M = 5

$E[C_1/C_0]$	(p)	x_u	$E[n_{Idle}]$	(p)	x_d
−0.02	(<0.02)	10	−0.09	(<0.08)	2
0.02−0.06	(0.02−0.06)	9	0.09−0.25	(0.08−0.20)	3
0.06−0.12	(0.06−0.11)	8	0.25−0.41	(0.20−0.29)	4
0.12−0.20	(0.11−0.17)	7	0.41−0.55	(0.29−0.36)	5
0.20−0.31	(0.17−0.24)	6	0.55−0.68	(0.36−0.41)	6
0.31−0.47	(0.24−0.32)	5	0.68−0.78	(0.41−0.45)	7
0.47−0.70	(0.32−0.42)	4	0.78−0.91	(0.45−0.49)	8
0.70−1.11	(0.42−0.55)	3	0.91−1.00	(0.49−0.52)	9
1.11−2.11	(0.55−0.76)	2	1.00−1.11	(0.52−0.55)	10
2.11−	(>0.76)	1	1.11−	(>0.55)	11

C. Control Algorithm

To provide run-time adaptive estimation reflecting the network dynamics, the estimation is performed using a moving average as follows:

$$E[C_1/C_0]_i \leftarrow (1-\alpha)\cdot E[C_1/C_0]_{i-1} + \alpha\cdot (C_1/C_0)_i. \tag{11}$$

To reduce overhead, we do not calculate the collision probability p or number of contending station N directly from the estimated C_1/C_0. Instead we prepare offline the threshold tuning tables indexed by θ_u (and θ_d) and $E[C_1/C_0]$, i.e., $f_u(\theta_u, E[C_1/C_0])$, $f_d(\theta_d, E[C_1/C_0])$. Thus, we can obtain adaptive thresholds $x_{u_{new}}$ and $x_{d_{new}}$ by simple run-time table lookup indexed by $E[C_1/C_0]$. For example, Table III is established for the initial thresholds (x_u=10, x_d=2). If measured $E[C_1/C_0]$ is 0.3, we select thresholds $x_{u_{new}} = 6$ and $x_{d_{new}} = 4$ as new operating thresholds.

The currently used thresholds x_u and x_d are also updated using a moving average as follows:

$$\begin{aligned} x_u &\leftarrow (1-\beta)\cdot x_u + \beta\cdot x_{u_{new}}, \\ x_d &\leftarrow (1-\beta)\cdot x_d + \beta\cdot x_{d_{new}}. \end{aligned} \tag{12}$$

VI. Performance Evaluation

A. Simulation Setup

In this section, we evaluate the performance of the proposed scheme via *ns-2* simulations [6]. We implemented our scheme in *ns-2* v2.31. For comparison, we also implemented ARF [22] and CARA [23]. All simulations are performed in an infrastructure WLAN with one AP and multiple stations. We simulate the IEEE 802.11b PHY. Offered traffic is constant bit rate (CBR) UDP traffic, and simulations are performed under saturated conditions. The moving average coefficients in Eqs. (11), (12) are set to α=0.1 and β=0.5.

B. Accuracy of Link-layer Sensing Technique

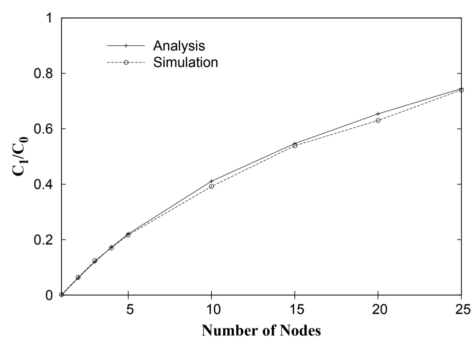
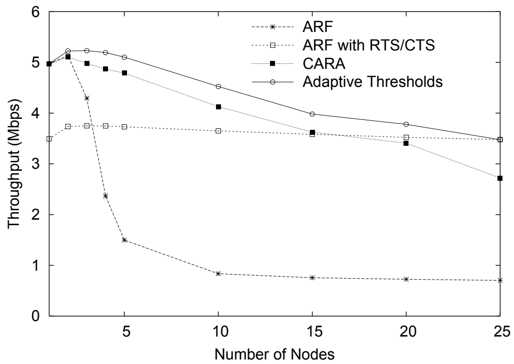


Fig. 10. C_1/C_0 as a function of N: Analysis vs. Simulation

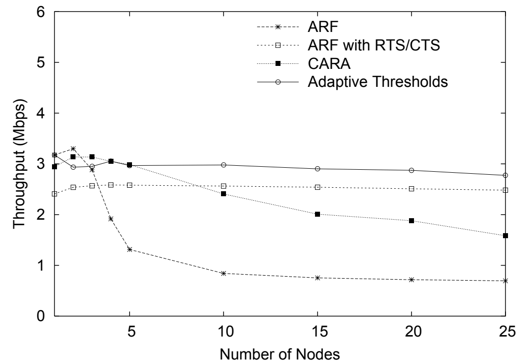
The predictive accuracy of the proposed link-layer sensing technique is essential to our threshold tuning. Thus, we first evaluate its accuracy by comparing the analytical results with *ns-2* simulations. Fig. 10 compares the values of C_1/C_0 obtained by analysis with simulation for 802.11b as the number of contending stations N is varied. From Fig. 10, we observe a close match between analysis and simulation results, which indicates that the link-layer condition (i.e., collision probability) is accurately estimated by our sensing technique.

C. Stationary Channel Condition

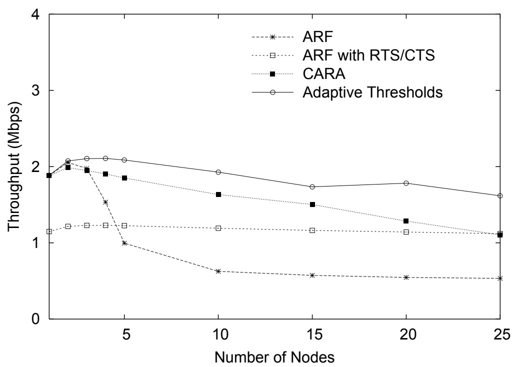
We now evaluate the impact of adaptive threshold tuning on throughput performance. We first consider the scenario where the channel is stationary. We compare the following schemes: (1)



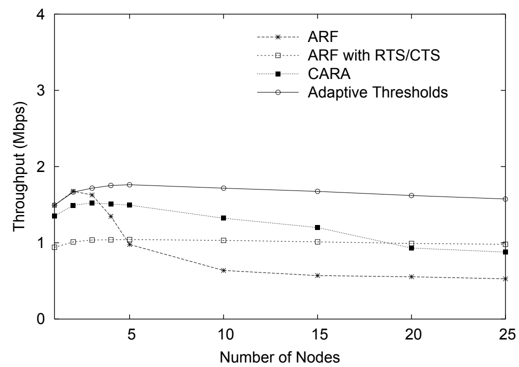
(a) 1000 bytes, SINR = 15dB



(b) 1000 bytes, SINR = 10dB



(c) 250 bytes, SINR = 15dB



(d) 250 bytes, SINR = 10dB

Fig. 11. Throughput comparison of our proposal (Adaptive Thresholds) against ARF, ARF with RTS/CTS, and CARA in stationary channel condition at which (a) SINR=15dB, 1000 bytes (b) SINR=10dB, 1000 bytes (c) SINR=15dB, 250 bytes (d) SINR=10dB, 250 bytes

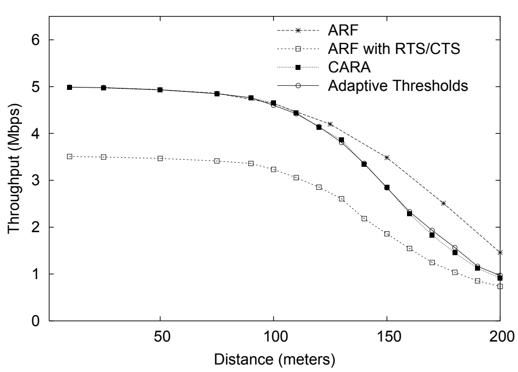
ARF, (2) ARF using the RTS/CTS exchange (referred as to ARF+RTS), (3) CARA and (4) our proposed link-layer adaptive scheme. The test schemes are compared with each other in terms of aggregate system throughput (in Mbps). As indicated in Section V, we set the consecutive success threshold (θ_u) to 10 and the consecutive failure threshold (θ_d) to 2 for ARF and CARA. We use empirical BER (Bit Error Rate) vs. SNR (Signal-to-Noise Ratio) curves [4] to set the FER (Frame Error Rate). The RTS/CTS frames are always transmitted at the lowest rate of 1 Mbps. We conduct the simulations under various channel states and different data frame sizes.

Fig. 11 presents the throughput performance of ARF, ARF+RTS, CARA, and our scheme as the number of stations is increased from 1 to 25. The throughput of ARF suffers as the number of stations increases. We observe that the cause of significant performance degradation (a bell shaped throughput curve) of ARF is that ARF cannot differentiate collisions from channel errors [15]. On the other hand, even as multiple access contention increases from 1 to 25, the throughput of ARF+RTS remains flat, which implies that ARF+RTS filters out collisions from channel errors using RTS/CTS exchanges. The results also show that our proposed adaptive threshold scheme prevents performance degradation in the high contention regime (i.e., large N). Moreover, the performance of our scheme is superior over a wide range of N. This is because our scheme mitigates the collision effect without the use of RTS/CTS handshake thus avoiding its overhead.

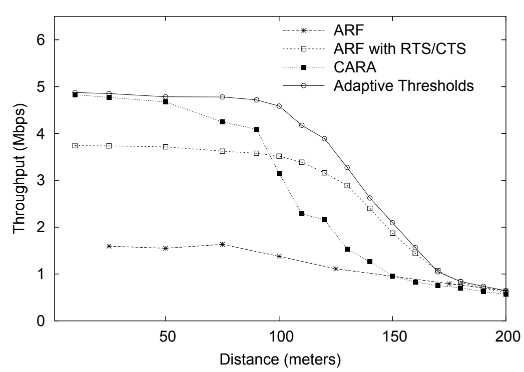
The overhead advantage of our method is expected to be more pronounced when considering the distribution of Internet packet size. According to a report from Cooperative Association for Internet Data Analysis (CAIDA) [26], actual Internet traffic has a peak at small size packets under 100 bytes and another peak at 1500 bytes corresponding to TCP's maximum transfer unit (MTU). The cost of RTS/CTS overhead amplifies for small packets. We show the performance for small packets (250 bytes payload) in Figs. 11(c) and (d).

D. Fading Channel Environment

We consider multi-path fading under which the channel condition varies over time. We use Ricean fading as the propagation model to simulate a time-varying wireless channel. Fig. 12



(a) N=1



(b) N=5

Fig. 12. Throughput comparison in Ricean fading channel (payload = 1000 bytes) for N=1 and 5

compares throughput of the test cases as a function of distance for (a) N=1 and (b) N=5. We see that when the number of stations is one (Fig. 12(a)), the performance of ARF and our scheme is almost the same since our method uses identical thresholds to ARF (there is no contention in this case). CARA's performance is slightly less than ours due to the overhead of selective RTS/CTS exchanges. The ARF+RTS scheme performs worst due to the overhead of RTS/CTS exchanges before every data transmission attempt. For the case of $N = 5$ (Fig. 12(b)), we see that the performance of ARF significantly decreases due to its missteps at higher contention levels. The result shows that our scheme significantly improves the performance of ARF and performs best in the benchmark suite. The improvement is achieved thanks to the small value of up-threshold x_u which enables our scheme to react to time-varying channel quickly. This result implies that the adaptive adjustment of the thresholds helps not only mitigate the collision effect but also improve responsiveness to the channel variation.

VII. Related Work

In recent years, rate adaptation has been an active research topic, and a number of algorithms [11], [20], [23], [24], [27], [29], [31], [32] have been proposed. Rate adaptation is left to vendors (i.e., is not specified in the IEEE 802.11 standard), yet its design plays a critical role in determining overall system performance [13], [15]. ARF [22] is the most popular rate adaptation, which has been extended in two directions; first, to improve its reactivity to time-varying channels [11], [24], [28], [29], and second, to deal with ARF's noise vs. collision differentiation problem [19], [23], [27]. An overview of existing methods can be found in [27] and [16]. To deal with the fast-fading and slow-fading wireless channels, the authors of [11] enhanced ARF to adaptively use a short probing interval and a long probing interval. In [29], a novel fast-responsive link adaptation scheme has been proposed, which directs the transmitter station's rate-increase attempts in a controlled manner such that the responsiveness of the link adaptation scheme can achieve minimum rate-increasing attempts. Kim et al. [23] proposed a modified ARF, called *Collision-Aware Rate Adaptation* (CARA), leveraging the per-frame RTS option. CARA exploits the fact that RTS frames are small and always encoded at the lowest rate. A RTS frame transmission failure is likely the result of collision whereas data frame transmission failures following a successful RTS/CTS handshake are likely due to channel error. CARA shows improved system performance thanks to its collision-awareness capability. The schemes proposed in [19], [32] use RTS/CTS mechanisms similar to CARA. Whereas most works in ARF have focused on improving performance through enhanced algorithms and protocol mechanisms, our previous work [13] focused on improving understanding of ARF's dynamics.

VIII. Conclusion

In this paper, we have proposed a new approach that mitigates the collision effect on the operation of rate adaptation in IEEE 802.11 WLANs by adaptively adjusting the rate-increasing and decreasing parameters. Unlike previous approaches based on explicit distinction between channel errors and collisions using costly RTS/CTS, we utilize link-layer feedback at the transmitter. We have developed a new link-layer sensing technique enabling the transmitter to acquire the current contention status. We have proposed a run-time algorithm to adaptively control the operating thresholds by simple run-time table lookup that captures the current network status obtained by our sensing technique. Through *ns-2* simulations, we have demonstrated that the proposed solution effectively offsets the collision effect, yielding significant performance gains compared to using fixed thresholds. The simulation results have also shown that our solution improves responsiveness to channel variation. While we demonstrate our solution in the context of ARF, the approach may be applicable to other sender-based schemes.

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