Fast-Responsive Link Adaptation for IEEE 802.11 WLANs

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Abstract— **The mechanism to select one out of multiple available transmission rates at a given time is referred to as *link adaptation*. The effectiveness of a link adaptation scheme depends on how fast it can respond to the wireless channel variation. In this paper, we propose a truly-adaptive fast-responsive link adaptation scheme for IEEE 802.11 WLANs (Wireless LANs). The key idea is to direct the transmitter station's rate-increasing attempts in a controlled manner such that the responsiveness of the link adaptation scheme can be guaranteed with minimum number of rate-increasing attempts. Since our scheme allows the transmitter station to make the link adaptation decision solely based on its local acknowledgment information, it does not require any change to the current 802.11 standard, thus facilitating its deployment with existing 802.11 devices. Our in-depth simulation shows that our scheme yields significantly-higher throughput than other existing schemes including single-rate schemes, the ARF (Auto Rate Fallback) scheme and its variants, in various fading channels.**

I. Introduction

In recent years, IEEE 802.11 WLAN (Wireless LAN) has become the dominant technology for indoor broadband wireless networking. The 802.11 PHYs (physical layers) provide multiple transmission rates by employing different modulation and channel coding schemes. For example, the original 802.11 standard [1] specifies three low-speed PHYs operating at 1 and 2 Mbps, and three high-speed PHYs were additionally defined as supplements to the original standard: the 802.11b PHY [2] supporting four PHY rates up to 11 Mbps at the 2.4 GHz band, the 802.11a PHY [3] supporting eight PHY rates up to 54 Mbps at the 5 GHz band, and the 802.11g PHY [4] supporting 12 PHY rates up to 54 Mbps at the 2.4 GHz band.

The mechanism to select one out of multiple available transmission rates at a given time is referred to as *link adaptation*. The effectiveness of a link adaptation scheme depends on how fast it can respond to the wireless channel variation, and different link adaptation schemes may affect the system throughput performance significantly. Due to the conservative nature of the link adaptation schemes implemented in most 802.11 devices, the current 802.11 systems are likely to show low bandwidth utilization. For example, our recent empirical study showed that certain 802.11g system only yields 11 Mbps throughput with the default link adaptation scheme, while we could achieve a much higher throughput at 35 Mbps with the same system by simply fixing the transmission rate at 54 Mbps.

There are two fundamental issues when designing a link adaptation scheme: *when to decrease the transmission rate and when to increase the transmission rate*, with the latter one a more challenging task. The transmitter station may increase its transmission rate using one of the following two approaches.

First, with aid of accurate channel estimation schemes to assess the wireless channel condition, the transmitter station knows when the channel condition improves enough to accommodate a higher rate, and then adapts its transmission rate accordingly. However, this type of approaches [5]–[9] usually require extra implementation effort and/or modifications to the current 802.11 standard. The authors of [10] presented an interesting link adaptation scheme based on channel estimation without requiring any standard change by utilizing RSSI (Receiver Signal Strength Indicator) measurements and the number of frame retransmissions. However, since this scheme operates under the assumption that all the transmission failures are due to channel errors, it does not perform well in multi-user environments, where many transmissions might fail due to collisions.

An alternative way of performing link adaptation is that the transmitter station makes the link adaptation decision solely based on its local Ack (Acknowledgment) information. In an 802.11 WLAN, an Ack frame is sent by the receiver upon successful reception of a data frame. It is only after receiving an Ack frame correctly that the transmitter assumes successful delivery of the corresponding data frame. On the other hand, if an Ack frame is received in error or no Ack frame is received at all, the transmitter assumes failure of the corresponding data frame transmission. Accordingly, the transmitter station may attempt increasing its transmission rate to "probe" the wireless channel condition upon consecutive successful Ack receptions. Apparently, this type of approaches [11], [12] require no changes to the 802.11 standard and, hence, are very easy to deploy with existing 802.11 devices.

In [11], the authors described the ARF (Auto Rate Fallback) link adaptation scheme used in Lucent Technologies' WaveLAN-II networking devices. It alternates between 1 and 2 Mbps transmission rates based on the results of a timing function and Ack counts. If two consecutive Ack frames are not received correctly by the transmitter, the second retry of the current frame and the subsequent transmissions are made at the lower rate and a timer is started. When either the timer expires or the number of successfully-received Ack frames reaches 10, the transmission rate is raised and the timer is canceled. However, if an Ack frame is not received for the very next frame transmission, the rate is lowered again and the timer is restarted. Since the ARF scheme attempts increasing the transmission rate at a fixed frequency of every 10 consecutive successful frame transmissions, it can not react quickly to fast wireless channel variations. On the other hand, it may overreact (i.e., attempt rate-increasing too often) when the wireless channel condition varies slowly. As an enhancement to the ARF scheme, the authors of [12] proposed to adaptively use a short probing interval and a long probing interval to deal with the fast-fading and slow-fading wireless channels. However, since the two probing intervals are heuristically set, this scheme works well only with certain patterns of the wireless channel variation.

Based on the above observations, in this paper, we propose a truly-adaptive fast-responsive link adaptation scheme that is able to adjust the probing interval dynamically to the wireless channel variation. The key idea is to direct the transmitter station's rate-increasing attempts in a controlled manner such that the responsiveness of the link adaptation scheme can be guaranteed with minimum number of rate-increasing attempts.

The rest of this paper is organized as follows. Section II describes the details of our proposed link adaptation scheme. Section III presents and assesses the simulation results and, finally, the paper concludes with Section IV.

II. The Proposed Link Adaptation Scheme

In this section, we present our link adaptation scheme from two fundamental aspects: *when to decrease the transmission rate and when to increase the transmission rate*.

A. When to decrease the transmission rate?

In general, the transmitter station should switch to a lower rate to transmit when the wireless channel condition degrades, which is normally indicated by frame transmission failures. However, considering the contention nature of the 802.11 DCF (Distributed Coordination Function) and the binary exponential backoff scheme used to resolve collisions, it is very likely that a single frame transmission failure is due to collision, while multiple consecutive failures are due to the deteriorated channel condition. Therefore, similar to the mechanisms described in [11]–[13], our link adaptation scheme requires the transmitter station to decrease the rate upon two consecutive transmission failures, as opposed to decreasing the rate immediately after a single transmission failure. Fig. 1 shows the pseudo-code of the simple algorithm used in our link adaptation scheme to direct the transmitter station's rate-decreasing actions. It starts/restarts whenever the station adjusts its transmission rate.

```
r_next := r_current;
r_low := the transmission rate next lower than r_current;

fail_count := 0;
while (r_next == r_current) {
    if (xmit_success(r_next) == 0)
    then   fail_count := fail_count + 1;
    else   fail_count := 0;      /* reset the counter */
    r_next := (fail_count == 2) ? (r_low) : (r_current);
}
```

Fig. 1. Pseudo-code of the algorithm to direct rate-decreasing in our proposed link adaptation scheme

B. When to increase the transmission rate?

The key component of a link adaptation scheme is to determine when to increase the transmission rate. A fast-responsive link adaption scheme shall react quickly to the improved wireless channel condition and make better use of the available bandwidth. Our objective is to direct the transmitter station's rate-increasing attempts in a controlled manner such that the responsiveness of the link adaptation scheme can be guaranteed with minimum number of rate-increasing attempts, hence maximizing the throughput.

Before describing the details of our proposed algorithm, we first present some observations and introduce a new concept called the *delay factor*.

1) Observations: Let t_0 denote the time instance when the transmitter station adjusts its transmission rate (due to variation of the wireless channel condition) and starts transmitting at rate $r_{current}$. Let t_x ($> t_0$) denote the time instance when the wireless channel condition improves so that the station is able to transmit at a higher rate of $r_{high} > r_{current}$.

Obviously, the more frequently the transmitter station attempts increasing its transmission rate, the more quickly the station is able to react to the improved channel condition, but more likely the station will experience more frame transmission failures due to pre-mature rate-increasing attempts and, consequently, waste channel utilization. So, there apparently is an inherent tradeoff. Fig. 2 shows a simple example to support the above statement. $\mathcal{S}_1$, $\mathcal{S}_2$, and $\mathcal{S}_3$ are three link adaptation schemes that direct the transmitter station to attempt rate-increasing upon, respectively, single, three, and six consecutive successful frame transmissions at rate $r_{current}$. As shown in the figure, $\mathcal{S}_1$ is clearly the most responsive scheme with minimum response delay ($\mathcal{D}_1$), but yields the most frame transmission failures ($\mathcal{N}_1 = 5$). In contrast, by decreasing the rate-increasing attempt frequency, $\mathcal{S}_2$ and $\mathcal{S}_3$ result in fewer frame transmission failures ($\mathcal{N}_2 = 2$ and $\mathcal{N}_3 = 1$) at the expense of larger response delays ($\mathcal{D}_3 > \mathcal{D}_2 > \mathcal{D}_1$).

2) Delay Factor: Based on the above observations, we quantify the responsiveness of a link adaptation scheme using a measure, called the *delay factor*, which is defined as

$$\mathcal{F}(t_x, \mathcal{S}) = \frac{\mathcal{D}(t_x, \mathcal{S})}{t_x - t_0}, \tag{1}$$

where $\mathcal{D}(t_x, \mathcal{S})$ is the resultant response delay when the transmitter station attempts rate-increasing according to link adaptation scheme $\mathcal{S}$. In the ideal case, the transmitter station has the perfect knowledge of the wireless channel variation and reacts without any delay. Therefore, the delay factor is zero. In general, the delay factor is a positive number, and the

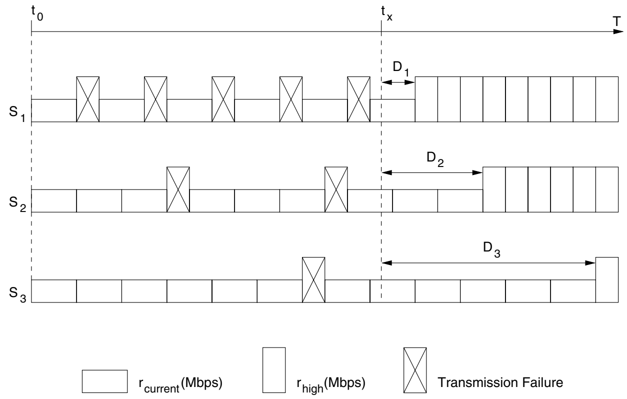

Fig. 2. Comparison of three link adaptation schemes

closer to zero the delay factor is, the more responsive a link adaptation scheme appears to be.

Note that the delay factor is not an absolute time measurement (in unit of seconds) but a percentage value (i.e., no unit). The reason for using a percentage-valued delay factor to assess link adaptation schemes is as follows. Consider the following two example scenarios. In the first scenario, the wireless channel condition varies frequently every 10 ms, and the transmitter station reacts to the improved channel condition with 5 ms response delay ($\mathcal{F} = 0.5$). In the second scenario, the wireless channel condition changes slowly every 100 ms, and the station also reacts with 5 ms response delay ($\mathcal{F} = 0.05$). Although both scenarios have the same response delay, the first one is clearly much worse than the second, because the wireless channel is under-utilized — frames are transmitted at lower than the highest achievable rates — for more than 50% of the time in the first scenario comparing to 5% in the second scenario. The delay factor is apparently a good indicator for such phenomena and, hence, a good metric to assess link adaptation schemes.

3) Key Idea: We propose a smart link adaptation scheme ($\mathcal{S}^*$) that can provide guaranteed responsiveness performance (i.e., a bounded delay factor) with minimum number of rate-increasing attempts. The design objective of our scheme can be formally described as follows. Given a target delay factor ($\mathcal{F}_{target}$), find the sequence of rate-increasing attempts to minimize the following weighted value:

$$\mathcal{W}(\mathcal{S}) = \int_{t_0}^{\infty} \mathcal{N}(t_x, \mathcal{S}) \cdot \mathcal{P}(\mathcal{F}(t_x, \mathcal{S})) \cdot f_{t_x} \cdot dt_x, \quad (2)$$

or in other words, find $\mathcal{S}^*$ such that

$$\mathcal{S}^* = \arg\min_{\mathcal{S}} \mathcal{W}(\mathcal{S}). \quad (3)$$

Recall that t_0 is the time instance when the transmitter station reacts to the variation of the wireless channel condition and starts transmitting at a newly-adjusted rate, and t_x ($> t_0$) is the time instance when the wireless channel condition improves so that the station is able to transmit at a higher rate. f_{t_x} represents the distribution of t_x. $\mathcal{N}(t_x, \mathcal{S})$ and $\mathcal{F}(t_x, \mathcal{S})$ are the corresponding number of rate-increasing attempts (between t_0 and t_x) and the resultant delay factor, respectively, when the link adaptation scheme $\mathcal{S}$ is adopted. $\mathcal{P}$ is a penalty function in the form of

$$\mathcal{P}(\mathcal{F}) = \begin{cases} 1 & \text{if } \mathcal{F} \leqslant \mathcal{F}_{target}, \\ \infty & \text{otherwise.} \end{cases} \quad (4)$$

Eq. (2) can be rewritten as

$$\begin{aligned} \mathcal{W}(\mathcal{S}) = & \int_{t_x \in \mathbb{R}^-} \mathcal{N}(t_x, \mathcal{S}) \cdot 1 \cdot f_{t_x} \cdot dt_x \\ & + \int_{t_x \in \mathbb{R}^+} \mathcal{N}(t_x, \mathcal{S}) \cdot \infty \cdot f_{t_x} \cdot dt_x, \end{aligned} \quad (5)$$

where $\mathbb{R}^-$ is the set of t_x time instances, given the link adaptation scheme $\mathcal{S}$, each of them corresponds to a delay factor equal to or smaller than $\mathcal{F}_{target}$, and

$$\mathbb{R}^+ = \overline{\mathbb{R}^-}. \quad (6)$$

Clearly, due to the extreme penalty enforced on situations when the resultant delay factor exceeds $\mathcal{F}_{target}$, in order to minimize $\mathcal{W}$, $\mathcal{S}^*$ must guarantee that

$$\mathbb{R}^+ = \emptyset. \quad (7)$$

Fig. 3 shows the pseudo-code of the algorithm used in our link adaptation scheme to direct the transmitter station's rate-increasing attempts. It starts/restarts whenever the station adjusts its transmission rate — recorded as t_0. $t_{attempt}$ represents the last-known time instance when the wireless channel remains the current condition, and it is initialized to $t_0 + \textit{xmit\_duration}(r_{current})$. As shown in the pseudo-code, we have

$$\begin{aligned} & t_{attempt} < t_x \\ \Longrightarrow \quad & \mathcal{D} = t_{now} + \textit{xmit\_duration}(r_{current}) - t_x \\ & \quad < t_{now} + \textit{xmit\_duration}(r_{current}) - t_{attempt} \\ & \quad \leqslant \mathcal{F}_{target} \cdot (t_{attempt} - t_0) \\ & \quad < \mathcal{F}_{target} \cdot (t_x - t_0) \\ \Longrightarrow \quad & \mathcal{F} = \frac{\mathcal{D}}{t_x - t_0} < \mathcal{F}_{target}. \end{aligned}$$

That is, the delay factor is always bounded under the target value, or equivalently, $\mathbb{R}^+ = \emptyset$. At the same time, the algorithm allows the station to transmit at the current rate as long as the delay-factor bound is not violated. In other words, any other link adaptation scheme with less rate-increasing attempts will not be able to guarantee the desired responsiveness performance. Therefore, we conclude that this algorithm achieves our design goal of providing the guaranteed responsiveness performance with minimum number of rate-increasing attempts.

4) Examples: We give simple examples to illustrate the above-described algorithm. Assume that

- $\textit{xmit\_duration}(r_{current}) = 2 \cdot \textit{xmit\_duration}(r_{high})$,
- $t_x \gg t_0$.

For different target delay factors ($\mathcal{F}_{target}$), our link adaptation scheme produces different rate-increasing attempt sequences

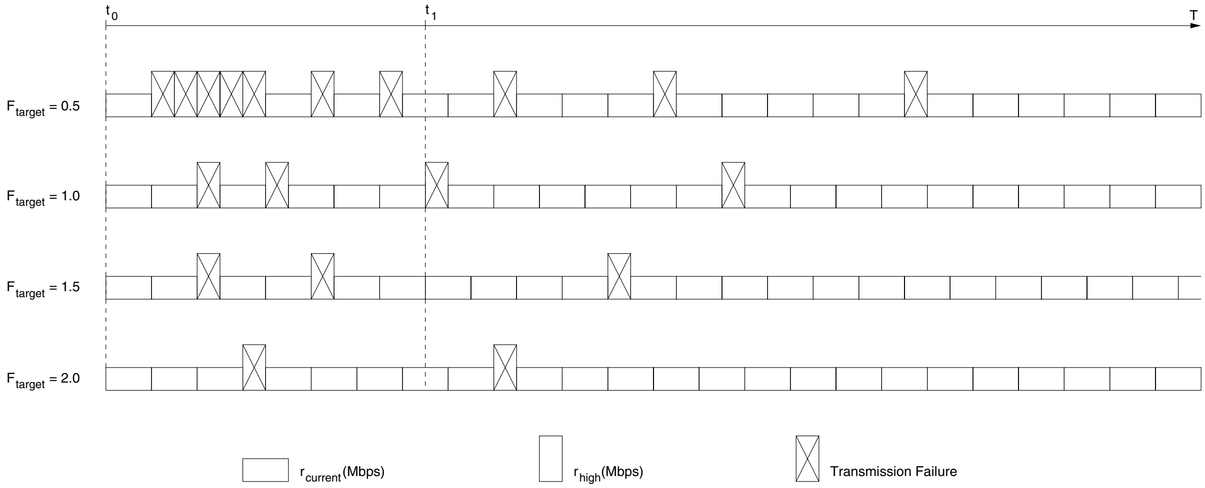

Fig. 4. Rate-increasing attempts directed by our proposed link adaptation scheme for different target delay factors

$r_{next} := r_{current}$;
$r_{high} :=$ the transmission rate next higher than $r_{current}$;
$t_0 := t_{now}$; $\quad t_{attempt} := t_0 + \mathit{xmit\_duration}(r_{current})$;

$\mathit{attempt\_success} := 0$;
while $(r_{next} == r_{current} \mid\mid \mathit{attempt\_success} == 0)$ {
  $t_{now} := t_{now} + \mathit{xmit\_duration}(r_{next})$;
  if $(\mathit{xmit\_success}(r_{next}) == 0)$
  then $t_{attempt} := t_{now} - \mathit{xmit\_duration}(r_{next})$;
  else {
    if $(r_{next} == r_{high})$
    then {
      $\mathit{attempt\_success} := 1$;
      break;
    }
  }
  if $\frac{t_{now} + \mathit{xmit\_duration}(r_{current}) - t_{attempt}}{t_{attempt} - t_0} \leqslant \mathcal{F}_{target}$
  then $r_{next} := r_{current}$;
  else $r_{next} := r_{high}$; /* rate-increasing attempt */
}

Fig. 3. Pseudo-code of the algorithm to direct rate-increasing attempts in our proposed link adaptation scheme

that are compared in Fig. 4. For instance, when $\mathcal{F}_{target} = 1.0$, after the station attempts its rate-increasing attempt at time t_1 and fails, it is allowed to transmit the next k frames at the current rate, where

$$k = \left\lfloor \frac{\mathcal{F}_{target} \cdot (t_1 - t_0) - \mathit{xmit\_duration}(r_{high})}{\mathit{xmit\_duration}(r_{current})} \right\rfloor = 6.$$

III. Performance Evaluation

In this section, we evaluate the effectiveness of our proposed link adaptation scheme using simulation.

A. Simulation Setup

We simulate an infrastructure-based 802.11a system, where eight transmitter stations are evenly spaced on a circle around the AP (Access Point) with the radius of r meters, and all the stations are static. Each transmitter station transmits with 15 dBm transmit power, and the background noise level is set to -93 dBm.

Note that multi-path fading can be observed even in the stationary WLAN environments due to movements of the surrounding objects. We simulate Rayleigh fading channel using the well-known Jakes' method [14], in which the complex channel gain is obtained by the sum of a finite number of oscillators with Doppler shifted frequencies, and a large (small) Doppler spread corresponds to a fast (slow) fading channel. The number of oscillators used in the simulation is 64. In addition, we use a log-distance path loss model with path loss exponent of four to simulate the indoor office environment.

We evaluate the following testing schemes: (1) our proposed link adaptation scheme; (2) the ARF schemes (ARF-10 and ARF-3) with a fixed probing interval of 10 and 3 successful frame transmissions, respectively; (3) the enhanced ARF scheme proposed in [12] using two probing intervals of 10 and 3 adaptively (ARF-3-10); and (4) single-rate schemes (Rx) using fixed PHY rate x Mbps ($x = 6, 9, 12, 18, 24, 36, 48, 54$). When implementing our proposed link adaptation scheme, we limit the number of consecutive successful frame transmissions at the same rate (before attempting rate-increasing) to *max_succ_count* = 50, in order to avoid potentially-long response delay when the wireless channel condition changes slowly. The testing schemes are compared with each other in terms of the aggregate system throughput (in Mbps).

We conduct the simulation under various channel fading conditions (via different Doppler spread values) and various network radius. Each simulation run lasts 100 seconds in the simulated system. Each transmitter station transmits in a greedy mode, i.e., its data queue is never empty, and all the data frames are transmitted without fragmentation. The frame size is 1024 octets unless specified otherwise.

B. Simulation results for different target delay factors

We first investigate how the selection of the target delay factor ($\mathcal{F}_{target}$) affects the throughput performance of our proposed link adaptation scheme. Assume that the network radius is 15 meters, and simulation results with different Doppler spread values are shown in Fig. 5.

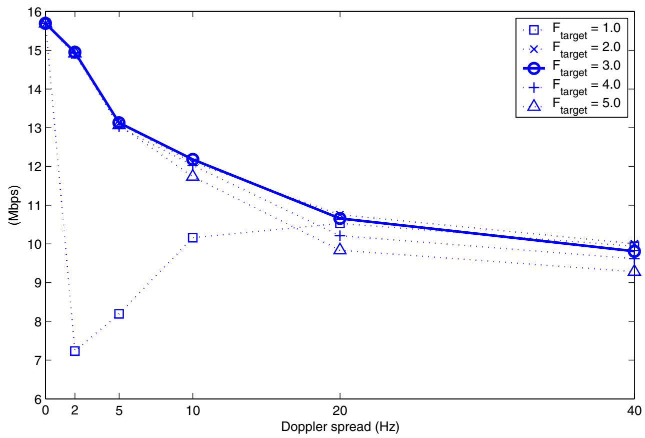

Fig. 5. Throughput comparison of our proposed link adaptation scheme with different target delay factors

As discussed in Section II, the delay factor reflects the responsiveness of a link adaptation scheme: the smaller the delay factor is, the more responsive a link adaptation scheme appears to be. Given a target delay factor, the design goal of our link adaptation scheme is to guarantee the corresponding responsiveness performance with minimum number of rate-increasing attempts, regardless of the variation pattern of the wireless channel condition.

Therefore, with a small target delay factor, our link adaptation scheme attempts increasing the transmission rate in a more aggressive manner so that it can react quickly to the fast-changing wireless channel condition. At the same time, if the wireless channel condition in fact changes slowly, it may result in many pre-mature rate-increasing attempts, and hence, waste channel utilization. As shown in the figure, with $\mathcal{F}_{target} = 1.0$, our link adaptation scheme yields very low throughput in slow-fading channels, while it has the best throughput performance in fast-fading channels. Similarly, when the target delay factor is set too large, the resultant link adaptation scheme appears less responsive and may not work well in fast-fading channels.

Simulation results suggest 3.0 to be a good value for the target delay factor because the resultant link adaption scheme works well under all different simulated fading conditions. Therefore, in the following simulation, we set $\mathcal{F}_{target} = 3.0$ for our link adaptation scheme.

C. Simulation results with various network radius

We compare the throughput performance of our link adaptation scheme (with $\mathcal{F}_{target} = 3.0$) against those of single-rate schemes with various network radius ($1 \leqslant r \leqslant 30$). The Doppler spread is fixed at 5 Hz and results are plotted in Fig. 6.

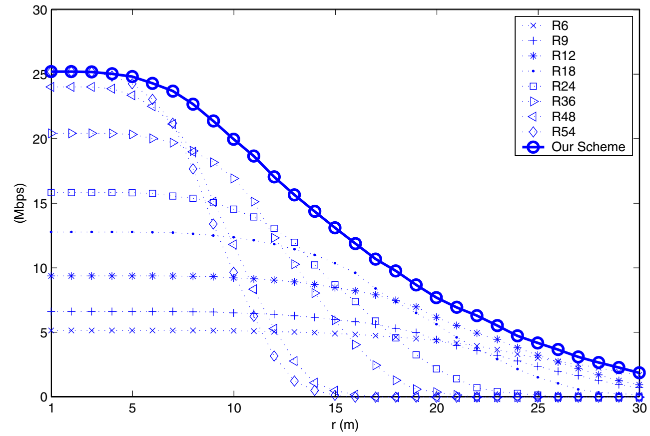

Fig. 6. Throughput comparison of our proposed link adaptation scheme against single-rate schemes

Dotted lines with various points correspond to different fixed transmission rates from 6 up to 54 Mbps, and the thick solid line with circle points represents our link adaptation scheme.

In general, the throughput decreases for all testing schemes and our proposed link adaptation scheme outperforms single-rate schemes in all simulated scenarios. R6 is the most conservative scheme of all. It transmits all the frames at the lowest 6 Mbps and, hence, results in the lowest throughput when r is small. At the same time, due to rate 6 Mbps' strong error-correcting capability, even when the transmitter station is far away from the AP, it is still able to communicate successfully with the AP. In comparison, R54 is the most aggressive scheme, which transmits all the frames at the highest 54 Mbps. R54 allows the transmitter station to make better use of the available bandwidth when r is small. However, due to rate 54 Mbps's poor error-correcting capability, the throughput degrades drastically as r increases. In fact, when $r > 15$, all the transmission attempts fail and throughput drops to zero. Other single-rate schemes can be viewed as compromises between R6 and R54.

We can see that, due to the fixed transmission rate, a single-rate scheme either suffers a reduced transmission range (for those sticking to high transmission rates) or degraded throughput (for those sticking to low transmission rates).

Our link adaptation scheme achieves the highest throughput in all simulated scenarios because of its adaptive use of (1) efficient high transmission rate when r is small, and (2) robust low transmission rate when r is large. In addition, due to fading effects, noticeable gaps can be observed between the throughput of our link adaptation scheme and the maximum-achievable throughput of single-rate schemes. Besides, our scheme does not compromise the transmission range since a far-away transmitter station can always lower its transmission rate to reach the AP.

D. Simulation results under various channel fading conditions

We now compare our link adaptation scheme (with $\mathcal{F}_{target}$ = 3.0) against ARF and its variants under various channel

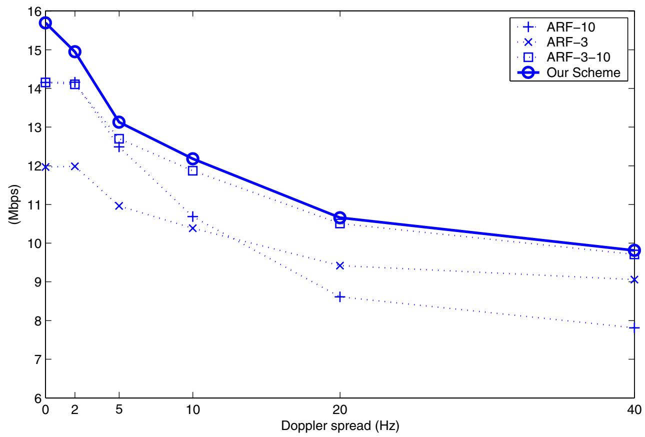

Fig. 7. Throughput comparison of various link adaptation schemes

fading conditions. The network radius is fixed to 15 meters and simulation results are shown in Fig. 7.

We have several observations. First, ARF-10 works well when the wireless channel condition changes slowly (i.e., Doppler spread values are small), while the throughput degrades significantly with increasing Doppler spread values. This is because, with a fixed large probing interval of 10 successful frame transmissions, ARF-10 does not react quickly to fast-changing wireless channel conditions. On the other hand, with a smaller probing interval of 3 successful frame transmissions, ARF-3 improves the throughput at large Doppler spread values. However, it does not perform well in slow-fading channels. This is because a small probing interval may result in too many pre-mature rate-increasing attempts and consequent frame transmission failures.

Second, without aid of channel estimation schemes, it is very difficult, if not impossible, to know the Doppler spread value of a wireless channel *a priori* and then decide the probing interval accordingly. Therefore, link adaptation schemes with fixed probing intervals will inevitably suffer throughput degradation when the wireless channel condition changes dynamically. In contrast, both ARF-3-10 and our link adaptation scheme adjust the probing interval adaptively and yield significantly-higher throughput than ARF-10 and ARF-3.

Third, our scheme consistently outperforms ARF-3-10 under all simulated scenarios. This is because our scheme adjusts the probing interval adaptively to the wireless channel variation from 1 up to 50 successful frame transmissions, as opposed to adapting between two heuristically-set values in ARF-3-10. In particular, as shown in the figure, significant performance differences between our scheme and ARF-3-10 can be observed when the wireless channel condition changes slowly, under which the probing interval of 10 successful frame transmissions might still be considered as too frequent.

IV. Conclusion and Future Work

IEEE 802.11 WLANs support multiple transmission rates, and in order to make better use of the available bandwidth of the time-varying wireless channel, it is very important to have a well-designed link adaptation scheme. In this paper, we describe a novel fast-responsive link adaptation scheme, which directs the transmitter station's rate-increasing attempts in a controlled manner such that the responsiveness of the link adaptation scheme can be guaranteed with minimum number of rate-increasing attempts. We compare the throughput performance of our scheme against those of single-rate schemes, the ARF (Auto Rate Fallback) scheme and its variants, under various channel fading conditions. Simulation results show that our scheme consistently outperforms others thanks to its truly-adaptive design nature.

Future work includes theoretical analysis of the relation between the target delay factor and the resultant throughput performance of our proposed link adaptation scheme and simulations under different network configurations.

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