An Adaptive Link Adaptation Scheme for Multi-rate Wireless LANs

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Abstract: - In this paper, we propose an efficient rate switching scheme for IEEE 802.11 Wireless LANs. The proposed scheme switches the transmission rate by the patterns of transmission successes and failures, and the measured signal strength of a recently received packet. Our simulation study shows that the proposed scheme shows better performance than existing rate adaptation schemes.

Key-Words: - link adaptation; multipath fading; multi-rate transmissions

1 Introduction

The adjustment of the transmission rate according to channel conditions is called rate switching and the rate switching mechanism is one of the fading mitigation methods used in the radio communication systems, with the goal of selecting the rate that will give the optimum throughput for the given channel conditions. The throughput is maximized if data could always be transmitted with the highest possible rate given the actual channel situation. If the rate is chosen too high, additional retransmissions are required which cause throughput degradation or even a total loss of communication. Choosing a too conservative data rate, however, also results in throughput degradation by not using the radio resources most efficiently. Therefore, an efficient dynamic rate adaptation is mandatory for achieving the highest possible system performance. Thus, the main issues for such a rate switching mechanism are the choice of the parameter to be used for the link quality estimation (e.g. packet error rate, signal to noise ratio, received signal strength, carrier to interference ratio, etc.), and how to select the appropriate rate from measurements of the selected parameter

2 Adaptive Auto Rate Fallback (AARF)

This section presents a novel multi-rate switching algorithm developed for stations operating under the fading channel conditions both in infrastructure mode and ad-hoc mode.

2.1 Channel Quality Estimation

Much of the other work on rate adaptation in wireless networks has assumed a cellular network. Although it may appear that such approaches are also applicable to wireless local area networks, several important differences exist in the context of IEEE 802.11 standard. For instance, conventional local area networks generally use half-duplex radios on single RF channels, making simultaneous sub-channel feedback impossible. Furthermore, conventional local area networks use distributed, contention-based medium access control protocols that require accurate estimates of packet transmission times for efficient operation (e.g. RTC/CTS). Thus, if transparent physical layer rate adaptation were to be employed, it would be difficult for the MAC layer to acquire accurate transmission time estimates, causing a decrease in efficiency. For these reasons, IEEE 802.11 recommends a rate switching function to be implemented at the MAC layer. With this reason, there is very limited information available at the MAC layer for the channel quality estimation.

In AARF, we use two metrics for the channel quality estimation: frame error patterns and received signal strength that are available at the MAC layer. We sophistically combine these two metrics to achieve the adaptability and the efficiency under the varying channel conditions.

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2.2 Algorithms for rate decreasing

We choose the indicator of channel quality degradation as frame error patterns which are used in ARF [17]. However, considering the contention nature of the 802.11 DCF, we must account for frame errors due to the frame collisions. The average number of collisions before the successful transmission is obtained as follows:

$$E[N_c] = \frac{1-(1-p)^M}{M \cdot p \cdot (1-p)^{M-1}} - 1. \tag{1}$$

Where M is the number of stations and the values of p is calculated from the following equation;

$$p = 1/(E[B]+1) \tag{2}$$

where E[B] is the average backoff time.

The expected value of consecutive collisions is shown in Figure 3.5 using the Equation (1). We observe from Figure 3.5 that 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, our rate switching scheme requires the transmitter station to decrease the rate upon two consecutive transmission failures. For the selection of appropriate rate after two consecutive transmission failures, we use the signal strength of recently received frames from the corresponding destination station or the received signal strength of CTS frame exchanged before the transmission of actual data frame. This can improve the adaptability under the degraded channel conditions significantly as we will show in the simulation study.

2.3 Algorithms for rate increasing

In ARF, there are two mechanisms to probe the next higher rate: ten consecutive ACKs and a timer. If ten consecutive ACKs are received or if the timer expires then the transmission rate is raised to the next higher rate. As the rate increasing condition, the ten consecutive ACKs may degrade the adaptability of rate switching scheme under the dynamic channel conditions. To improve the responsiveness, a timer is started every time the transmission rate has changed. Thus, if the timer expires before ten consecutive ACKs, the rate switching scheme transmit a frame at the next higher rate as a probe. If the probing frame gets corrupted during its transmission time, the transmission rate remains unchanged and the timer is started again. But this periodic probing may degrade the throughput performance under the steady channel conditions because of its wasted probing frame.

To overcome this periodic probing at a higher rate and the sequential rate shifting in ARF, we use again the signal strength of recently received frames or the received signal strength of CTS frame exchanged before the transmission of actual data frame. This can improve the throughput performance under the steady channel conditions significantly as we will compare in the Section 5.

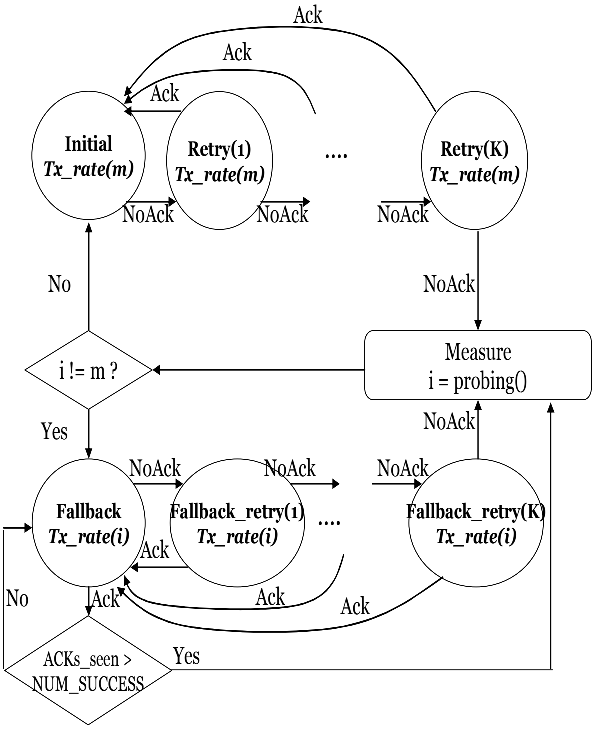


Fig.1 Operations of AARF

2.4 Protocol operations

Now, we describe the proposed scheme, called adaptive auto rate fallback (AARF) scheme, where a sending station keeps track of the signal strength of the last frame received from each destination. We define ACKs_seen and ACKs_missed values to represent the number of consecutive ACKs received well and the number of consecutive ACKs missed, respectively. Both of the values are used to change the current TX rate. If ACKs_missed value exceeds a predefined threshold value (NUM_FAILED), the sender thinks that the quality of the link to the receiver has been deteriorated and thus it updates its transmission rate of the following transmissions for the receiver. At this point, AARF uses the signal strength of the last frame received from the receiver for determining the new transmission rate. On the other hand, if ACKs_seen value exceeds a predefined value (NUM_SUCCESS), the sender thinks that the quality of the link to the receiver has been improved and thus it updates its transmission rate for the receiver. AARF also uses the signal strength of the last frame received from the receiver for determining the new transmission rate.

Figure 3.6 shows a state transition diagram of AARF's operation, where m is the number of transmission rates supported by a particular WLAN standard. Thus, in case of IEEE 802.11b, the value of m is 4. We assign the highest transmission rate to the value of Tx_rate(m) so that MAC tries to send a DATA frame using the highest transmission rate first. There are three state classes in AARF – Initial, Fallback, and Measure – as shown in Figure 3.6. In the Initial state, the sender transmits a DATA frame to its destination at the maximum rate (e.g., 11 Mbps in 802.11b or 54 Mbps in 802.11a) and the sender maintains three values – 'the current TX rate (Tx_rate)', 'the number of consecutive ACKs seen (ACKs_seen)', and 'the number of consecutive ACKs missed (ACKs_missed)'. Each time the sender missed an ACK frame, it transits to the subsequent Retry(i), i=1…k, state. At the Retry(k) state, if the sender missed an ACK frame (which means that k+1 consecutive ACK frame losses have been occurred), AARF transits to the Measure state. At a Retry(i) state, if the sender receives an ACK frame for the DATA frame, it goes back to the Initial state as shown in Figure 3.6.

3 Analysis of AARF

3.1 Analytical model of AARF

The AARF can be modeled as a 4-states FSMC model as shown in Figure 5.6. We use the approach of [58] but additionally consider combined effect of level crossing rate (LCR) and average fade duration (AFD) in calculating the FSMC parameters. The definitions of LCR and AFD are given Equation 5.5 and Equation 5.7 respectively in Section 5.1. The expected throughput of AARF is derived as follows:

$$\begin{aligned} E[Thru] = {} & \pi_4 \times \rho_{\max}[4] \times (1 - PER_4) \\ & + \pi_3 \times \rho_{\max}[3] \times (1 - PER_3) \\ & + \pi_2 \times \rho_{\max}[2] \times (1 - PER_2) \\ & + \pi_1 \times \rho_{\max}[1] \times (1 - PER_1) \end{aligned} \quad (3)$$

where π_i : the steady state probability that system is in transmitting at Tx[i], i=1,…,4, . $\rho_{\max}[i]$: the system capacity at each transmission rate Tx[i], and PER_i : the packet error rate at each transmission rate Tx[i].

The capacity of IEEE 802.11 WLAN $\rho_{\max}[i]$ is given in[].

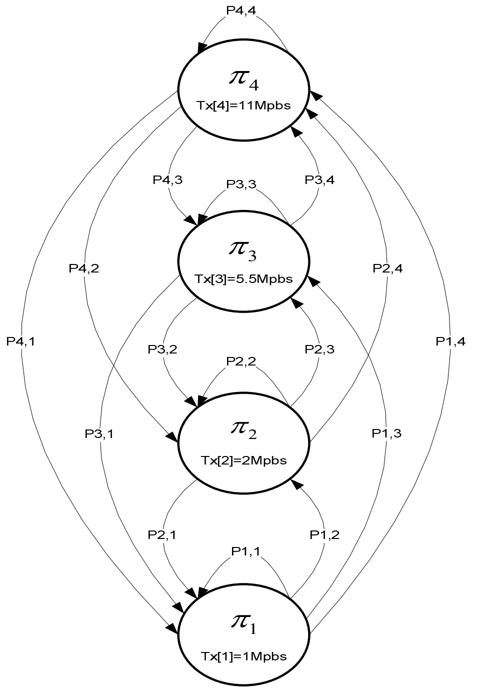


Fig.2 Finite-state Markov chain model of AARF

From the Equation (5.5), we drive the approximate maximum throughput of each transmission rate as follows:

$$\rho_{\max}[i] = Tx[i] \cdot \rho_{\max}, \quad where \quad i = 1,...,4. \quad (4)$$

The transmission rate of Tx[i] is given in Figure 5.6. The packet error rate PER for modulation scheme m is associated with bit error rate BER as follows:

$$PER_i = 1 - (1 - BER_i)^{8L}, \quad where \quad i = 1,...,4. \quad (5)$$

The bit error rate BERi for the transmission rate Tx[i] can be derived from its modulation methods and the channel conditions. The state transition probability of FSMC in Fig.2 is the main jobs to derive the

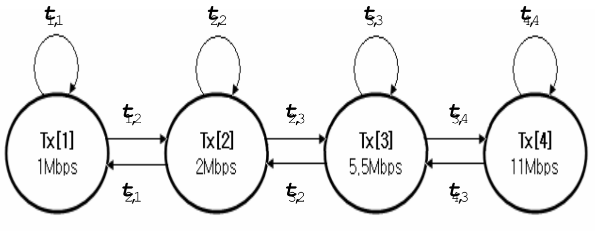


Fig. 3 Reduced Finite-state Markov model of AARF

numerical throughput results as we will formulate it in the following subsection.

3.2 Formulation under slow changing channel conditions

To make the analytical model derived above more tractable for performance analysis, we make the following assumptions. We first assume that the Rayleigh fading channel is slow enough that the received SNR remains at a certain level for the time duration of a channel symbol. Furthermore, the channel states associated with consecutive symbols are assumed to be neighboring states:

$$p_{i,j} = 0, \forall \, |i-j| > 1 \, . \tag{6}$$

In other words, each state can have no more than three outgoing and incoming transitions. With these assumptions, the finite-state Markov chain model of Figure 5.6 can be reduced to Figure 5.7. Now, consider a communication system with a transmission rate of Rt symbols per seconds. There are, on the average,

$$R_t^{(k)} = R_t \times p_k \tag{7}$$

symbols per second transmitted during which the channel is in state Tx[k] with the probability pk. Due to the slow fading assumption, we can conclude that the level crossing rate in Equation (5.5) at Ak and Ak+1 is much smaller than the value of $R_t^{(k)}$.

The transition probability $t_{k,k+1}$ can then be approximated by the ratio of the expected level crossing at Ak+1 divided by the average symbols per second the SNR falls in the interval associated with state Tx[k]. Similarly, the transition probability $t_{k,k+1}$ can be approximated by the ratio of the expected level crossing at Ak divided by the average symbols per second the SNR falls in the interval associated with state Ak . Specifically, let Nk, k=1,2,3,…,K-1, be the expected number of times per second the received SNR passes downward across the threshold Ak. Then from Equation (5.3), we have

$$N_k = \sqrt{\frac{2 \cdot \pi \cdot A_k}{\rho}} \cdot f_m \cdot \exp\left\{-\frac{A_k}{\rho}\right\} . \tag{8}$$

The Markov transition probabilities are then approximated by

$$t_{k,k+1} \approx \frac{N_{k+1}}{R_t^{(k)}}, k = 0,1,2,...,K-2 \tag{9}$$

and

$$t_{k,k-1} \approx \frac{N_k}{R_t^{(k)}}, k = 0,1,2,...,K-1 \tag{11}$$

Finally, we get the state transition probabilities of AARF under the slow changing channel condition:

$$\begin{bmatrix} 1-\frac{N_2}{R_t^{(1)}} & \frac{N_2}{R_t^1} & 0 & 0 \\ \frac{N_2}{R_t^{(2)}} & 1-\frac{N_2}{R_t^{(2)}}-\frac{N_3}{R_t^{(2)}} & \frac{N_3}{R_t^{(2)}} & 0 \\ 0 & \frac{N_3}{R_t^{(3)}} & 1-\frac{N_3}{R_t^{(3)}}-\frac{N_4}{R_t^{(3)}} & \frac{N_4}{R_t^{(3)}} \\ 0 & 0 & \frac{N_4}{R_t^{(4)}} & 1-\frac{N_4}{R_t^{(4)}} \end{bmatrix} \tag{12}$$

From the Equation (5.18), the steady state probability π_k is derived as follow:

$$\begin{aligned} \pi_k &= \int_{A_k}^{A_{k+1}} \frac{1}{\rho} \cdot \exp\left\{-\frac{a}{\rho}\right\} da \\ &= \exp\left\{-\frac{A_k}{\rho}\right\} - \exp\left\{-\frac{A_{k+1}}{\rho}\right\} \end{aligned} \tag{13}$$

where π_k is the steady state probability that the channel state is in Tx[k] in Figure 5.7. Thus we get the steady state probabilities of AARF under the slow changing channel condition:

Given the channel state partitions Ak, and Doppler shift frequency, we can easily estimate the expected throughput of AARF with Equation (5.12) and with the reduced analytical model in Figure 5.7 under the slow changing channel condition.

$$[\pi_1\ \pi_2\ \pi_3\ \pi_4] = \begin{bmatrix} \exp\left\{-\frac{A_0}{\rho}\right\} - \exp\left\{-\frac{A_1}{\rho}\right\} \\ \exp\left\{-\frac{A_1}{\rho}\right\} - \exp\left\{-\frac{A_2}{\rho}\right\} \\ \exp\left\{-\frac{A_2}{\rho}\right\} - \exp\left\{-\frac{A_3}{\rho}\right\} \\ \exp\left\{-\frac{A_3}{\rho}\right\} - \exp\left\{-\frac{A_\infty}{\rho}\right\} \end{bmatrix}^T \tag{14}$$

4 Performance Comparison

We performed our performance evaluation study of the proposed scheme by using ns-2 [5, 6] and compared it with RBAR [4], ARF [3], and multiple single rates supported by the IEEE 802.11 [2].

4.1 Slow Changing Channel Conditions

We model the channel as two-ray ground propagation model and use the network model consisting of an access point and a mobile node. During simulation runs, a mobile node moves in 10m increments over the transmission range and, each distance is fixed for a 100s of transmission of CBR data over a single UDP connection. Here, data are generated at a rate of 8 Mbps and are sent in 1460 byte packets. Figure 3 shows the throughput performance when MAC transmits data using two-way handshake mode (DATA-ACK). For comparison purpose, the performances of ARF [3] and RBAR [4] are also included. As shown in the Figure 3, the proposed HARF scheme shows better performance than RBAR in all distance ranges, which is due to the fact that RBAR should transmit RTS and CTS frame at one of the transmission rates in basic rate set (usually 1 or 2 Mbps). HARF outperforms ARF when the distance is 100m or more. This is due to the fact that, when the channel condition is good, ARF increases its transmission rate to the next higher data rate, while HARF determines the new data rate by the recently measured signal strength value, and thus HARF reflects the channel condition more rapidly. Figure 4 shows the simulation results carried under same conditions as in Figure 3 except that all DATA frames are transmitted using four-way handshake mode. HARF and RBAR show same results. This is because HARF uses the rss_value of CTS frame to find an optimal transmission rate using the similar method used in RBAR. At the transmission rates of 5.5 Mbps and 2 Mbps, ARF shows poor performances because of its frequent transmission trials at a higher rate when the number of consecutive ACKs exceeds its NUM_SUCCESS value. HARF avoids ARF's frequent transmission trials using the Measure state. The handshake mode of IEEE 802.11 MAC is controlled by the RTSThreshold parameter which is closely related to the size of frame. If the fame size is larger than RTSThreshold, it is transmitted using four-way handshake mode to prevent fame corruption from intervening transmissions. From the simulation results, ARF is expected to outperform other schemes under the various traffic conditions consisting of mixed fame sizes.

4.2 Fast Changing Channel Conditions

We model the channel as a Ricean fading propagation model [7] and use the same network configuration as in the slow changing channel conditions. We performed simulations for five different speeds, 2, 4, 6, 8, and 10 m/s to study the algorithms' behaviors under the extreme fading fluctuation scenarios. Figure 6 shows performance results generated for a UDP connection carrying CBR traffic that was generated at the rate of 8 Mbps and sent in 1460 byte packets. HARF shows the best performance in all speeds. Under the fast changing channel conditions, the channel state estimation of RBAR exchanging RTS-CTS frames may cause frequent rate switching to

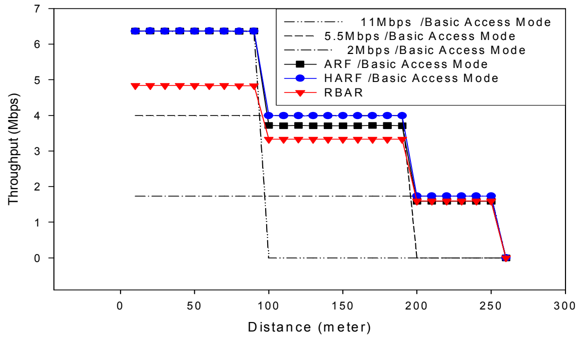


Fig.4 Slow Changing Channel Conditions (Two-way handshake)

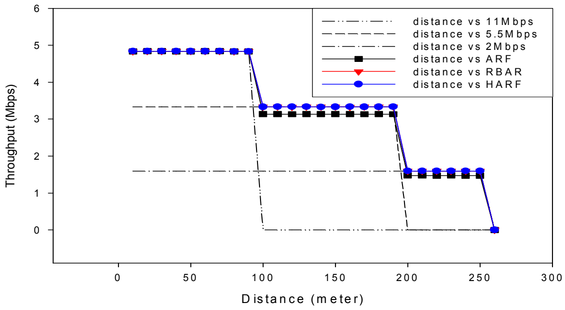
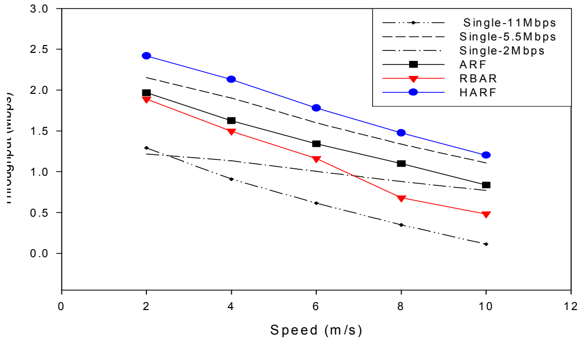


Fig.5 Sow Changing Channel Conditions (Four-way handshake)



ig. 6 Fast Changing Channel Conditions (UDP raffic)

other transmission rates, which can result in transmission failures due to the shortened channel coherence time. HARF suppresses frequent rate switching during fading fluctuations. For example, HARF allows rate switching only when the channel has been in good state during the time of consecutive NUM_SUCCESS ACKs and still the received signal strength value is good enough for switching the data rate to a higher rate.

Figure 7 shows performance results for a TCP connection. The throughput performances of all schemes are degraded as compared to UDP traffic, which can be attributed to TCP's sensitivity to packet losses during fading fluctuations. HARF also outperforms all other schemes over the all mobile speed ranges. The performance of RBAR is slightly better than that of ARF in TCP traffic scenario. For the single rate schemes, 5.5 Mbps transmission rate has achieved better results than 2 Mbps and 11 Mbps transmission rates do.

5 Conclusion

The proposed HARF scheme switches the transmission rate by the patterns of transmission successes and failures, and the measured signal strength of a recently received packet. The proposed scheme does not switch data rates gradually, but it switches its data rate according to the recently received signal strength value. The proposed scheme increases the speed of rate adjustment and shows better performance under the time varying channel conditions.

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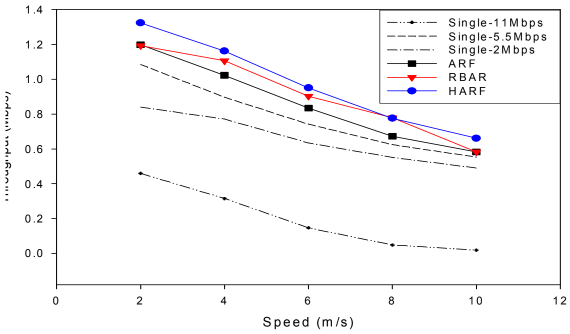

Fig. 7 Fast Changing Channel Conditions (TCP traffic)

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