RARA: Rate Adaptation Using Rate-adaptive Acknowledgment for IEEE 802.11 WLANs

Hakyung Jung*, Kideok Cho*, Yongho Seok†, Taekyoung Kwon* and Yanghee Choi*

* School of Computer Science and Engineering, Seoul National University, Seoul, Korea
†Information and Technology Lab., LG Electronics Institute of Technology, Seoul, Korea
E-mail: *{hkjung, kdcho, tk, yhchoi}@mmlab.snu.ac.kr, †yhseok@lge.com

Abstract— **The IEEE 802.11 standards support multiple bit rates at the physical layer so that stations can maximize the system performance by controlling the transmission rate responding to the conditions of underlying time-varying channels. This paper proposes a novel scheme, termed as *Rate Adaptation using Rate-adaptive Acknowledgment (RARA)*. The key idea of RARA is to regulate the ACK transmission rate as a means to dictate the sender to adjust the data transmission rate. Compared with previous works, the proposed scheme can react quickly to the prevailing conditions by the receiver-based decision while inducing marginal overhead. Simulation results show that the RARA consistently outperforms other rate adaption schemes.**

I. INTRODUCTION

The 802.11 standards provide multiple transmission rates at the physical layer by employing different modulation schemes and/or error correcting codes. Since the radio environment rapidly changes due to fading and mobility, the channel quality seen by both mobile and stationary stations varies substantially over time. In order to maximize the system throughput, stations must adapt to the dynamically changing environments by adjusting transmission rates accordingly. For example, when channel conditions are favorable, it is better to choose the high transmission rate to increase throughput. On the other hand, the low transmission rate should be used for poor link conditions for better error/noise resilience. A mechanism to select the optimum transmission rate at a given time is referred to as *rate adaptation*.

The 802.11 requires that response frames, i.e., acknowledgment (ACK) or CTS frames, be transmitted at a bit rate that is constrained by two rules: (i) the transmission rate of an ACK frame should be less than or equal to that of the preceding data frame, and (ii) the ACK frame is transmitted at a rate selected from the basic rate set . We call this *legacy ACK rate*. For instance, the basic rate set in 802.11b comprises 1 and 2 Mbps, which can be configured by each basic service set (BSS)[1].

The rationale behind this approach is that these response frames should be transmitted as fast as possible while preserving error-free reception under the current channel condition. The receiver, however, may transmit the ACK frame at a next lower rate than the legacy ACK rate, referred as *next lower ACK rate*. Consequently, the transmission time increases slightly but the ACK frame being short causes only negligible (or marginal, depending on the performance) impact on the system performance. Therefore, the receiver can use the next lower ACK rate to inform the transmitter of the channel condition information for the next data frame.

In this paper, we introduce a novel rate adaptation scheme, named as *Rate Adaptation using Rate-adaptive ACK (RARA)*. The key idea of RARA is for the receiver to transmit an ACK frame at the next lower ACK rate if the channel condition, as measured from the received data frame, is estimated good enough to increase the data transmission rate. Upon receiving the ACK frame at the next lower ACK rate, the sender increases the data transmission rate to the next higher rate.

Our approach has the following advantages.

- It is the receiver that estimates the channel quality and selects the appropriate rate at a given time, which maintains the fact that the channel quality can be best observed at the receiver [1].
- When the channel quality becomes favorable, the transmission rate is immediately increased by the sender at the time of ACK frame reception.
- Compared with previous closed-loop rate adaptation schemes, informing the transmitter of the next transmission rate by adjusting ACK transmission rate is not costly, as will be discussed later.

The remainder of this paper is organized as follows. First, related work is presented in Section II. The details of RARA and its issues are described in Sections III and IV, respectively. Section V presents the simulation results. We conclude this paper in Section VI.

II. RELATED WORK

Research on rate adaptation in 802.11 WLANs has a rich history. Depending on whether feedback from a receiver is used or not, the existing rate adaptation schemes can be categorized into *open-loop* and *closed-loop* approaches.

In the open-loop category, rate adaptation schemes determine the transmission rate without the feedback from the receiver. Most schemes in this approach estimate the channel quality based on the recent ACK reception history at the sender (e.g. [2], [3], [4], [5]). In the 802.11 standard, after receiving the data frame successfully, the receiver transmits

---

[1] BSS maintains a basic rate set, which is a list of rates that must be supported by every station joining the BSS.

an ACK frame to the sender; thus, the sender can conclude that the channel condition is degraded when consecutive ACK frames are not received successfully. Other schemes in this category decide the transmission rate based on the local channel condition that is estimated while ACK frames are received [6].

Open-loop solutions, however, do not perform well in certain scenarios. For example, although the former presumes that successive transmission failures are due to the poor channel condition, frame losses can also be caused by interference from hidden stations or collisions. Moreover, although the latter assumes that the wireless link between the sender and receiver is symmetric, it is known that wireless links are highly asymmetric, especially in indoor environments [7].

In the closed-loop category, the receiver measures the channel quality and gives back the desired transmission rate to the transmitter via modified RTS/CTS messages (e.g. [1], [8]). After receiving an RTS frame from the transmitter, the receiver conveys the desired transmission rate via a modified CTS frame. Due to the accurate channel estimation by receivers, those schemes usually achieve a considerable performance gain. Since closed-loop solutions require an information exchange between two stations, the signaling overhead and modification of the standard are inevitable. Thus, reducing the amount of overhead while minimizing the modification of standards is the important design issue in the closed-loop approach.

Clearly, previous closed-loop proposals modifies the standard frame format to convey the channel information; thus, they are not compatible with legacy 802.11 devices. In addition, exchanging RTS/CTS frames can be costly especially when hidden stations do not exist. Moreover, RTS/CTS exchanges are not used in the most of practical infrastructure-based WLANs. In this paper, we propose controlling the transmission rates of ACK frames as a means to convey the channel information, so that the transmitter can adjust the data transmission rate accordingly. Although adjusting the ACK transmission rate does not conform to the 802.11 standard in a strict sense, it does not modify the frame format, which allows the backward compatibility with legacy 802.11 devices. In addition, adjusting the ACK transmission rate incurs much less overhead compared with the above closed-loop solutions.

III. THE PROPOSED RATE ADAPTATION SCHEME

There are in general two components of a rate adaptation scheme, i.e., when to decrease and when to increase the transmission rate. In this paper, we focus only on the latter issue, which is more challenging. Hereafter, a sender is the station that transmits a data frame and a receiver is the station that replies with an ACK frame right after the data frame.

A. When to increase the data rate?

The RARA algorithm at the receiver is presented in Algorithm 1. D_{curr} means the bit rate of the current data frame that is just received. $LegacyAckRate$ in the pseudo code indicates the 802.11-compliant transmission rate of an ACK, which is the highest possible rate in the basic rate set (BRS), but no faster than the rate of D_{curr}. After receiving a data frame successfully, the receiver estimates the channel condition. If the receiver deems that the current channel quality is good enough to make the sender switch to the next higher data rate, it signals the sender via adjusting the ACK transmission rate not in accordance with the 802.11 standards. The ACK transmission rate is adjusted as described in Algorithm 1.

The following paragraph pertains to the case when the radio link is good enough to increase the bit rate of data frames. First, when the data frame was transmitted at the highest rate, there is no need for the receiver to trigger the increase of data transmission rate; thus ACK frames are always replied to the sender at the legacy ACK rate regardless of channel estimation results. Second, if the data rate was transmitted equal to or faster than the highest rate in basic rate set, the ACK frame is transmitted at the next lower ACK rate. Third, if the data transmission rate was lower than the highest rate in the BRS, the next higher rate than the legacy ACK rate can be used for signaling instead of the next lower rate. One might be concerned the third case, which may make the ACK frame transmission unsuccessful. However, the channel condition is already estimated to be acceptable to transmit at the next higher rate by the receiver. Moreover, the size of an ACK frame is normally much smaller than that of a data frame; thus, with the same bit error rate condition, ACK frames are likely to be successfully delivered compared to data frames.

The RARA algorithm at the sender is presented in Algorithm 2. It is triggered whenever the sender receives an ACK frame successfully. Upon receiving the ACK frame at other than the legacy ACK rate, the sender increases the data rate to the next higher rate. Meanwhile, if the ACK frame is received by the sender at the legacy ACK rate as specified in 802.11, the data transmission rate is left untouched.

RARA is illustrated with the ARF scheme in Fig. 1. Assume that station S_1 transmits data frames to station S_2, and the channel condition is time-varying and 802.11b is used for the physical layer. Backoff intervals are omitted for simplicity. Successful transmissions are depicted by blank rectangles and transmission failures due to channel errors are depicted by crossed rectangles. In this example, RARA employs the operation of the ARF to determine when to decrease the rate.

Algorithm 1 Pseudo-code of RARA at the receiver

```
$D_{curr}$: the current transmission rate of the data frame
$A_{next}$: the transmission rate of the ACK frame

if channel condition is acceptable to increase $D_{curr}$ then
    if $D_{curr}$ is the highest transmission rate then
        {do nothing}
        $A_{next} \Leftarrow LegacyAckRate$;
    else if $D_{curr} \geq$ highest transmission rate in BRS then
        $A_{next} \Leftarrow$ the next lower rate than $LegacyAckRate$;
    else
        $A_{next} \Leftarrow$ the next higher rate than $LegacyAckRate$;
    end if
end if
```

Algorithm 2 Pseudo-code of RARA at the sender

```
$A_{curr}$: the transmission rate of the received ACK frame
$D_{prev}$: the transmission rate of the previous data frame
$D_{next}$: the transmission rate of the next data frame

if $A_{curr} \neq LegacyAckRate$ then
    $D_{next} \Leftarrow$ the next higher rate than $D_{prev}$;
else
    do nothing;
end if
```

At the beginning, both schemes lower the transmission rate after experiencing two consecutive transmission failures since the channel condition at the receiver was poor. After a while the channel quality becomes favorable to transmit at the 11 Mbps, however, ARF cannot increase the transmission rate timely because it needs 10 consecutive successful transmissions for an increase-attempt. On the other hand, the RARA adapts to the channel promptly. In RARA, after receiving third data frame successfully, station S_2 sends a signal to station S_1 to increase the data transmission rate by lowering the ACK transmission rate to 1 Mbps. As a result, a station with the RARA scheme is able to transmit more frames using higher rates. We can see that RARA can transfer 13 frames earlier than ARF i.e., $t_1 < t_2$.

B. When to decrease the data rate?

It should be noted that the RARA algorithm can be combined with any rate adaptation schemes to decide when to decrease the transmission rate. By way of illustration, we adopt either ARF or CARA [5]. The operation of ARF is based on the local ACK reception history at a sender. If two consecutive ACKs are not received correctly by the sender, the sender assumes that transmission failures were due to degraded channel condition, thus decreasing the data transmission rate to the next lower rate. However, this simple operation does not perform well in contention-prone environments where transmissions may fail frequently due to collisions. To take collisions into account, CARA exchanges RTS/CTS frames adaptively when a data frame transmission fails. The underlying rationale is that exchanging RTS/CTS frames before transmitting data frames can reduce transmission failures due to collisions.

IV. INCORPORATION OF RARA INTO 802.11

A. Media Access Timing in 802.11 DCF

The 802.11 standard provides virtual carrier-sensing by the network allocation vector (NAV). The value in the duration field is used to reserve the medium until the current transmission sequence is finished. Stations set the NAV timer according to the duration value, and decrement it by 1 for each time slot. When the NAV is nonzero, the virtual carrier-sensing function deems that the channel is busy regardless of the result of physical carrier-sensing; when the NAV reaches zero, the virtual carrier-sensing function indicates that the channel is idle.

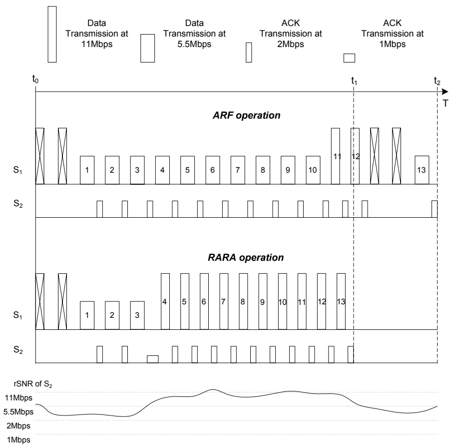


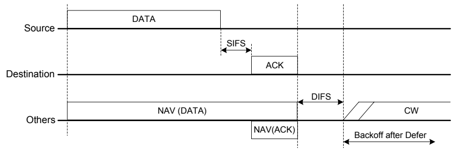
Fig. 1. Illustration of RARA and ARF in the time-varying channel.

Fig. 2(a) is a timing diagram illustrating the successful transmission of a data frame. When a data frame is transmitted, all stations hearing the data frame adjust their NAV timers based on the duration field value, which consists of the data frame transmission time, the SIFS, and the ACK transmission time. In this way, the NAV prevents other stations from accessing the medium until the sequence of transmissions completes. After frame transmissions has completed and the DIFS has elapsed, stations can attempt to transmit.

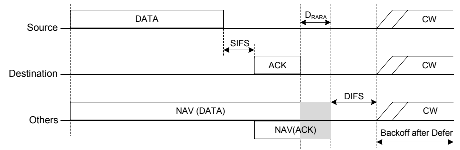
B. Modified NAV operation

In RARA, the ACK frame transmission time may be prolonged for signaling the increase of data transmission rate. The 802.11-compliant sender, however, calculates the value of the duration field assuming that the receiver will reply the ACK frame at the legacy ACK rate according to 802.11 standards. As a result, the actual time to complete the sequence of transmissions can be larger than the time specified in the duration field; the ACK frame transmission can be interfered by other stations accessing the channel after their NAV timers expire.

To ensure that the sequence of transmissions (the data and the ACK frames) is atomic and not interfered, we suggest that the sender calculate the value of the duration field in a conservative manner by assuming that the following ACK frame will be transmitted at the next lower ACK rate. Fig. 2(b) shows how this modified (or enlarged) NAV value protects the sequence from interference or collision. Let D_{RARA} denote the time difference between the 802.11-compliant NAV and the NAV extended by RARA. Upon hearing the data frame or ACK frame, other stations adjust their NAV timers based on the NAV value. Note that there are cases in which the next lower ACK rate will not be used by the receiver, e.g. the sender uses the highest bit rate, or the sender uses a bit rate which is lower than the maximum in the basic rate set. In such cases, the sender calculates the NAV according to the 802.11 standard. Hence there is no waste of airtime.



(a) NAV operation in IEEE 802.11



(b) Modified NAV operation for RARA

Fig. 2. Timing diagram for comparison of legacy NAV operation with modified operation

C. Deferred access

Suppose the receiver replies with the ACK at the legacy ACK rate. Both the sender and the receiver will start the backoff earlier than others by D_{RARA} because other stations deems that the channel is still busy due to the over-estimated NAV. Thus, it can lead to unfairness among stations. To prevent this issue, we suggest that both the sender and the receiver defer channel contention by D_{RARA} before DIFS. In particular, if the next lower ACK rate is used, both the sender and the receiver do not need to defer D_{RARA} since the sequence of transmissions will be finished by the time the NAV extended by RARA expires.

This modified NAV operation results in the overhead in overall system throughput, since all stations have to defer accessing the medium during D_{RARA} compared to the 802.11-compliant operations. However, this overhead is inevitable to be embodied in closed-loop rate adaptation. Obviously, our scheme causes less overhead compared with previous closed-loop solutions, which use additional control frame exchange such as RTS/CTS frames for signaling [1].

V. PERFORMANCE EVALUATION

In this section, we evaluate RARA using the *ns-2* simulator with the enhanced DCF module supporting 802.11b PHY.

A. Simulation Setup

Our simulation experiments are configured as follows unless specified otherwise. We assume that 1 and 2 Mbps are in the basic rate set. We simulate the indoor office environment; thus, we use a log-distance path-loss model with the path-loss exponent of four . We also use the Ricean fading model with Ricean K factor of 3 dBm to consider the multi-path fading effect in the indoor wireless channel [9]. Most of our network parameters were drawn directly from the Intersil document [10], including power constraints, sensitivity thresholds, etc. We use LLC/IP/UDP as the upper layer protocol suite, and the MAC layer payload length is 1500 bytes. All stations are static and always have a packet to transmit. Each station transmits frames for 200 seconds and results of the last 100 seconds are taken into account to avoid initial dynamics. We repeated this run 20 times and averaged them.

We evaluate the following testing schemes in terms of the throughput (in Mbps): (1) our proposed scheme combined with ARF and CARA (referred to as RARA and RARA+CARA, respectively); (2) the ARF scheme (referred to as ARF), (3) the adaptive-ARF scheme [3] (referred to as AARF), (4) the CARA scheme (referred to as CARA).

B. Results with various distance

We first evaluate RARA in the simple one-to-one topology, in which a station continuously transmits frames to the other station. Both stations are static and the distance between the two stations is varied between 10 to 60 meters.

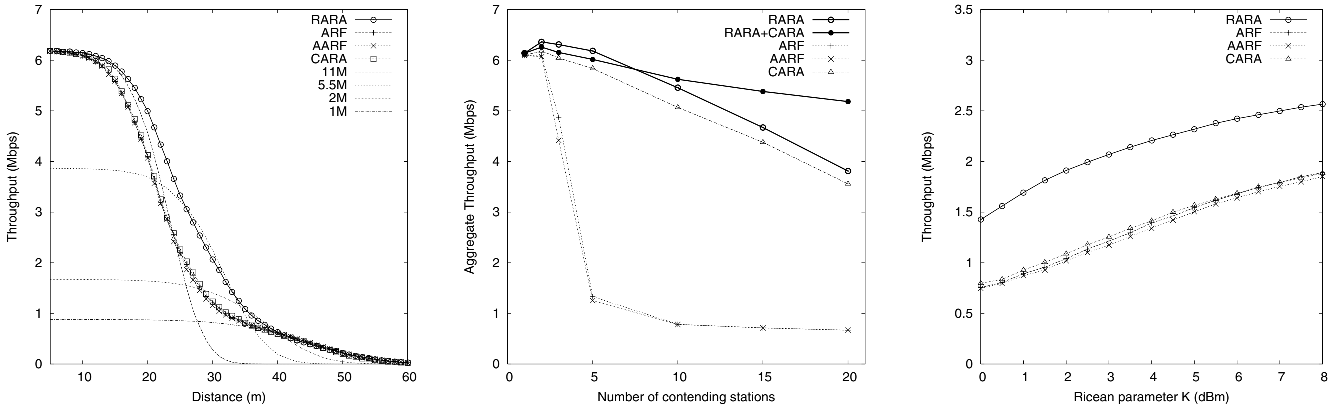
Fig. 3(a) shows the average throughput of testing schemes: ARF, AARF, CARA, single-rate schemes, and RARA. In general, the throughput of all the schemes decreases as the distance between two stations increases, and the throughput curves of rate adaption schemes roughly follow the outer envelope of those of the single-rate schemes.

We have two observations from Fig. 3(a). First, RARA achieves better throughput than the other schemes over the entire range. Moreover, the throughput curve of RARA is higher than the best throughput combined from the single-rate schemes around the boundary of two consecutive single-rate schemes since RARA is able to adapt quickly to the time-varying wireless channel. Second, the throughput curve of RARA is slightly below that of single-rate scheme at several distances such as from 26 to 33 meters. This is because the extended NAV value and deferred access in RARA cause the overhead compared to normal single-rate schemes, but the difference is marginal.

C. Results with varying number of contending stations

In [5], it is revealed that the rate adaptation scheme should consider the collision effect not to malfunction when transmission failures happen frequently due to collisions. To study how effectively RARA deals with collisions, we now evaluate the performance of testing schemes in a star topology. In this topology, a varying number of contending stations are equi-distantly placed on a circle centered around the AP with the 10 meter radius.

Simulation results are plotted in Fig. 3(b). Both RARA and RARA+CARA obtains higher performance than the others. Especially, the performance of ARF and AARF is degraded severely as the number of contending stations increases compared with CARA and RARA schemes. There are two main reasons for the poor throughput of ARF and AARF. First, both ARF and AARF cannot differentiate collisions from the channel errors, thus decreasing the transmission rate unnecessarily. Second, in order for both ARF and AARF to increase the transmission rate, 10 or more consecutive successful transmissions should occur. These events, however, are not likely to happen due to frequent collisions. Between CARA and RARA, since CARA uses the same algorithm as



(a) Various distance (b) Varying number of contending stations (c) Varying Ricean parameter K

Fig. 3. Throughput comparison of our proposed scheme (RARA and RARA+CARA) against ARF, AARF, CARA, and single-rate schemes.

the ARF to decide when to increase the transmission rate, it yields the lower throughput than RARA or RARA+CARA.

We now compare the performance of RARA with RARA+CARA. Since RARA+CARA causes the additional overhead of RTS/CTS frame exchanges, RARA performs better when the number of contending stations is small. However, the throughput becomes turned over as the the number of contenders increases because the collision-probing technique of CARA reduces collisions by using RTS/CTS frame exchanges adaptively.

D. Results with varying Ricean parameter K

Now, we evaluate the effect of Ricean fading with parameter K on the performance of testing schemes. In Ricean distribution, parameter K represents the strength of line-of-sight component of the received signal. For $K = 0$, the Ricean distribution becomes equivalent to the Rayleigh distribution, in which the channel has no line-of-sight component: only reflected signals are received and the overall channel quality is degraded. As K increases, the line-of-sight components become dominant and hence the overall signal quality is getting better.

Fig. 3(c) depicts the throughput of each scheme in one-to-one topology according to Ricean parameter K. The distance between two stations is fixed to 30 meters. We have two observations from Fig. 3(c). First, every scheme performs better as the parameter K increases because they exploit the improved channel condition as K increases. Second, RARA achieves higher throughput for the entire range of K than the others. This indicates that RARA maintains relatively stable performance not only in good channel condition but also in poor channel condition.

VI. CONCLUSION

In this paper, we proposed a novel rate adaptation scheme, termed as *Rate Adaption using Rate-adaptive ACK (RARA)*. In RARA, a receiver of a data frame measures the signal-to-noise ratio (SNR) of the received frame. If the SNR is high enough to increase the transmission rate of the sender, the receiver controls the ACK transmission rate as a means to dictate the sender to adjust the data transmission rate. RARA adapts to the time-varying wireless channel quickly owing to the accurate and instant feedback. We carried out *ns-2* simulation experiments in comprehensive scenarios and found that RARA achieves better throughput than other rate adaptation schemes. In the future, we plan to analytically study RARA, and evaluate its performance against other closed-loop approaches such as RBAR.

REFERENCES

[1] G. Holland, N. Vaidya, and P. Bahl,“A rate-adaptive MAC protocol for multi-Hop wireless networks,” in Proceedings of the 7th annual international conference on Mobile computing and networking. Rome, Italy: ACM Press, 2001.

[2] A. Kamerman and L. Monteban, “WaveLAN/sup R/-II: a high-performance wireless LAN for the unlicensed band,” Bell Labs Technical Journal, vol. 2, pp. 118-133, 1997.

[3] L. Mathieu, M. Mohammad Hossein, and T. Thierry, “IEEE 802.11 rate adaptation: a practical approach,” in Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems. Venice, Italy: ACM Press, 2004.

[4] S. H. Y. Wong, H. Yang, S. Lu, V. Bharghavan, “Robust Rate Adaptation for 802.11 Wireless Networks,” in Proceedings of the 12th annual international conference on Mobile computing and networking Los Angeles, CA, USA: ACM Press, 2006.

[5] J. Kim, S. Kim, S. Choi, and D. Qiao, “CARA: Collision-aware Rate Adaptation for IEEE 802.11. WLANs,” in Proceedings of the IEEE INFOCOM, Barcelona, Spain, 2006.

[6] J. P. Pavon and C. Sunghyun,“Link adaptation strategy for IEEE 802.11 WLAN via received signal strength measurement” in 2003 IEEE International Conference on Communications (Cat. No.03CH37441), 2003, pp. 1108-13 vol.2.

[7] K Papagiannaki, M Yarvis, WS Conner, “Experimental Characterization of Home Wireless Networks and Design Implications,” in Proceedings of the IEEE INFOCOM, Barcelona, Spain, 2006.

[8] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly,“OAR: an opportunistic auto-rate media access protocol for ad hoc networks” Wireless Networks, vol. 11, pp. 39-53, 2005.

[9] M. Carroll and T. A. Wysocki, “Fading characteristics for indoor wireless channels at 5 GHz unlicensed bands,”in Procedings of SympoTIC 2003, pp. 102-105.

[10] Intersil, “HFA3861B; Direct Sequence Spread Spectrum Baseband Processor”, January 2000.