Rate Adaptation Algorithms for IEEE 802.11 Networks: A Survey and Comparison

Saâd Biaz, Shaoen Wu
{sbiaz, wushaoe}@auburn.edu
Shelby Center for Engineering Technology, Suite 3101
Computer Science and Software Engineering Department
Auburn University
107 Dunstan Hall, Auburn University, AL, 36849-5347, USA

***Abstract*— Rate adaptation is the determination of the optimal data transmission rate most appropriate for current wireless channel conditions. It consists of assessing channel conditions and accordingly adjusting the rate. Rate adaptation is fairly challenging due to wild channel conditions fluctuations. In the last decade, rate adaptation for IEEE 802.11 networks has been extensively investigated. This paper presents a comprehensive and detailed study of the advances of rate adaptation schemes proposed for IEEE 802.11 networks, and summarizes their characteristics. We also categorize these rate adaptation schemes based on their support of loss differentiation and their methods to sense the channel conditions. Then, this paper compares the performance of three representative schemes through simulations. Finally, open issues for rate adaptation are raised.**

I. Introduction

Wireless medium suffers from unstable channel conditions (e.g. signal fading due to distance, frame collision from simultaneous transmissions, and interference from other sources). For nodes supporting multiple data rates, rate adaptation is indispensable to optimally exploit the scarce wireless resources under such instable channel conditions. Rate adaptation consists of assessing the wireless channel conditions and selecting the most appropriate data rate.

Rate adaptation for IEEE 802.11 networks has been studied at length through the last decade. The proposed rate adaptation schemes can be roughly grouped into two generations. Most first generation rate adaptation schemes [1]–[6] implicitly assume that all frame losses are due to channel degradation with limited congestion losses, and thus do not differentiate between congestion and channel degradation losses. Such an assumption is valid as long as the MAC layer deploys some collision avoidance mechanism (e.g. RTS/CTS control frames) to eliminate or minimize congestion losses. Some rate adaptation schemes [7]–[9] even rely on such RTS/CTS control frames to adapt the data rate and minimize congestion losses.

However, RTS/CTS frames may constitute a substantial overhead. IEEE 802.11 standard recommends that RTS/CTS control frames be used only when data frames are large(default threshold is 2347 bytes). Therefore, RTS/CTS control frames are not used in most realistic scenarios. This limits all RTS/CTS-based rate adaptation schemes. Even with RTS/CTS, congestion losses may still occur and mislead these first generation data rate adaptation schemes. Most data rate adaptation schemes systematically respond to frame loss by decreasing their data rates. While such a response is appropriate for channel degradation, it is not for a collision loss for two reasons: 1) a lower rate may exacerbate medium congestion because of longer frame transmission duration and wider transmission range (more collision); 2) a lower rate is wasteful and unnecessary as channel conditions may well support a higher rate.

In recent years, researchers designed second generation rate adaptation schemes [10]–[14] that diagnose the cause of a loss and appropriately adjust the data rate. Most of them are designed to work in realistic scenarios without RTS/CTS. Although some of these schemes [11], [12] still require the use of RTS/CTS in case of loss, others [13], [14] do not.

To the best of our knowledge, there is little work so far that surveys rate adaptation schemes and summarizes their characteristics. This paper serves such a purpose. The primary contributions of this paper are:

- We comprehensively investigate and categorize rate adaptation schemes proposed for IEEE 802.11 networks. Characteristics and common features are summarized.
- We evaluate and compare through simulation the performance of three representative schemes.
- We raise open issues on rate adaptation, which could further advance this field.

The rest of this paper is organized as follows. We survey, categorize, and analyze in Section II the representative data rate adaptation schemes with highlighting their characteristics and common features. Section III presents the performance comparison of representative schemes using simulation. Section IV discusses the open issues. Finally, we conclude this paper in Section V.

II. Survey of Rate Adaptation Algorithms

This section surveys rate adaptation schemes proposed for IEEE 802.11 networks. Generally, rate adaptation schemes estimate current channel conditions based either on signal-to-noise ratio (SNR) or frame loss ratio. For the latter, channel

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conditions are assessed based on the number of successive successful transmissions or the observation of the loss rate over a sliding time window. Some of these rate adaptation schemes require the use of RTS/CTS.

In general, there are two possible causes of frame loss: channel fading or collision. In the rest of this section, we partition rate adaptation schemes into the two generation: First generation does not differentiate loss causes while the second generation does. Within each generation, schemes are further classified based on the channel condition estimator they use: frame loss or SNR.

A. *Rate Adaptation Algorithms without Loss Differentiation*

This section presents the rate adaptation schemes without loss differentiation categorized in two groups: frame loss based or signal strength based.

1.) Frame Loss Based Rate Adaptation

Auto Rate Fallback (**ARF**) by Kamerman and Monteban [1] is the earliest rate adaptation scheme for IEEE 802.11 based wireless networks. Kamerman and Monteban proposed it for the Lucent Wave-II wireless LAN adapters. It is simple and intuitive. A sender starts transmission at the basic (lowest available) data rate (2 Mpbs in IEEE 802.11b) and triggers a timer. If either the timer expires or the sender succeeds for N (a constant threshold) consecutive transmissions, the sender increases its data rate r_{old} to a new data rate r_{new}, and the timer is reset. If the first transmission at the new rate r_{new} fails *immediately* after the data rate is increased, the sender falls back to the prior rate r_{old}. The data rate is also decreased when the sender fails twice consecutively. *ARF* considers the frame loss ratio as the indicator of the channel conditions. It adjusts the rate based on the number of consecutive successful transmissions.

Lacage *et al* proposed *Adaptive Auto Rate Fallback* (**AARF**) [2] to improve performance in stable environments. Unlike *ARF* keeping the rate increase threshold constant (N), *ARRF* adaptively adjusts this threshold. More specifically, a sender increases its data rate r_{old} to a new rate r_{new} after N consecutive successful transmissions. If the first transmission at this new rate r_{new} fails, the sender falls back on the prior rate r_{old} and doubles the threshold to $2N$ for the next rate increase. Otherwise, i.e., the first transmission at the new rate succeeds, the threshold is reset. With such adaptive threshold updates, *AARF* increases the time interval between rate increases over a stable channel and produces fewer rate fluctuations than *ARF*.

As the earliest implemented open source rate adaptation on a Linux driver, **Onoe** [3] was developed by MadWifi organization for wireless adapters with Atheros chips. It is a credit based algorithm and tries to find the best data rate with a loss ratio less than 50%. *Onoe* adjusts the rate at the end of each 1000 ms cycle based on collected transmission statistics. Therefore, *Onoe* is insensitive to bursty losses and irresponsive to fast changes in wireless channel changes. The detailed algorithm *Onoe* is illustrated in the flowchart on Figure 1.

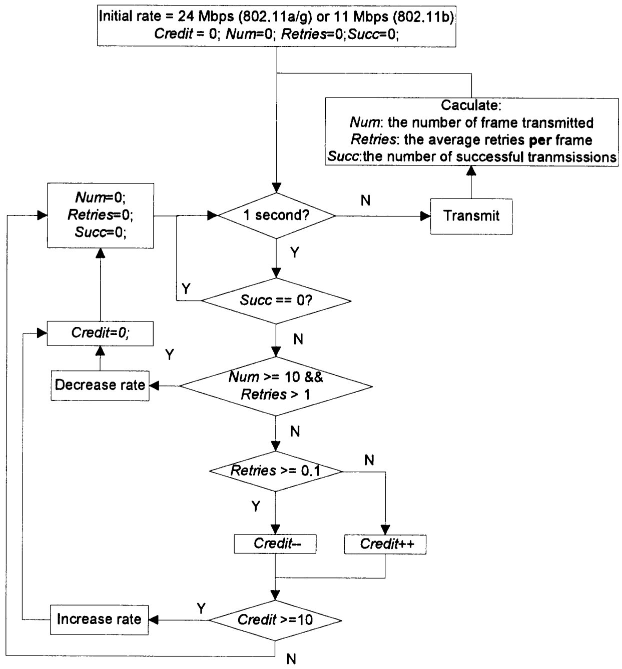

Fig. 1. Onoe Flowchart

Rate adaptation scheme **SampleRate** [4] by Bicket is also based on transmission statistics over a sliding window period. *SampleRate* adjusts its rate to the bit-rate that would achieve the smallest *average transmission time* in the last sampling period. The transmission time for a frame is defined as the time to send this frame successfully (till acknowledged), which includes the time for retransmissions and backoff stipulated by IEEE 802.11. *SampleRate* starts transmitting at the highest rate and decreases the rate immediately if it experiences four consecutive transmission failures. This scheme calculates the average transmission time *per* frame for different rates every 10-second period. To explore potential better channel conditions in the sampling period, *SampleRate* randomly selects one from all other rates whose average transmission time is less than the average lossless transmission time of the rate in use for every tenth frame. The following example illustrates this strategy: In IEEE 802.11b, for a packet of 1500 bytes, the lossless transmission time are about 1.873, 2.976, 6.834 and 12.995 ms respectively for the four data rates 11, 5.5, 2 and 1 Mbps (from Figure 5-1 in [4]). With a couple of transmissions, suppose the average transmission time at 11 Mpbs is 3.276 ms, which is larger than the lossless transmission time (2.796 m) with 5.5 Mbps. Then for the tenth packet, *SampleRate* transmits at 5.5 Mbps hoping that such a transmission might take less average transmission time. Using the rates with smallest average transmission time, *SampleRate* seeks to achieve the best average throughput performance in the long term.

With *SampleRate*, we close this section on rate adaptation schemes that are based on loss ratio to estimate channel conditions. In the following, we focus on rate adaptation schemes that are based on the signal-to-noise ratio or the signal strength.

2.) Signal Strength/SNR Based Rate Adaptation

Receiver Based Auto Rate (**RBAR**) [7] by Holland, Vaidya, and Bahl is the first rate adaptation that takes advantage of the control frames RTS/CTS transmitted at the basic rate. *RBAR* modifies IEEE 802.11 standard in two aspects: 1) the channel reservation in the header of RTS/CTS is represented by packet size and rate, instead of the standard transmission time; 2) a proposed message RSH precedes the data frame to finalize the tentative reservation information in CTS. The source station Src selects a heuristic rate (for instance, the rate of last successful transmission) and includes it and the packet size in RTS. When the destination station Dst gets RTS, it retrieves the signal-to-noise ratio (SNR) from physical layer and translates it to a data rate that can be supported by current channel conditions. Then Dst embeds the selected data rate and the data packet size in the CTS frame header. All stations sensing this CTS frame can calculate the *tentative* channel reservation time from the packet size and rate. Receiving the rate information in CTS, the Src makes the final decision about the rate to use. This proposal relies on the use of RTS/CTS.

Heusse *et al* [15] observed a performance anomaly in IEEE 802.11 multi-rate networks: all stations achieve almost the same throughput despite different rates. This is due to the equal probability of all stations with CSMA/CA to access the shared wireless channel in spite of their perceived channel conditions. This is the so called throughput fairness. But this fairness hurts the performance of those stations with high rates and the overall network. Another option is to achieve temporal fairness among stations: each station gets almost equal transmission time rather than equal throughput. *Opportunistic Auto Rate* (**OAR**) [8] by Sadeghi *et al* tackles this challenge. *OAR* probes the rate through the exchange of RTS/CTS exactly as *RBAR* does. However, it differs from *RBAR* in its opportunistic transmission of data frames. After a source Src selects the rate, *OAR* transmits multiple consecutive frames depending on the selected rate: 5 for 11 Mbps, 3 for 5.5 Mbps and 1 for 2 Mpbs. *OAR* takes advantage of the fragmentation mechanism in IEEE 802.11 to transmit these multiple consecutive frames. Fragmentation allows to keep the channel until all fragments are sent. *OAR* delivers time fairness and also improves the throughput performance with less average overhead of contention time and RTS/CTS per frame.

Scheme *Full Auto Rate* (**FAR**) [9] by Li *et. al* attempts to achieve full data rate adaptation. The authors contend that, as for receiver based protocols, like *RBAR*, if the RTS/CTS is transmitted at a higher data rate, rather than the basic rate, better performance should be achieved because transmission at basic rate underutilizes the wireless channel. In *FAR*, an idle station overhears frames from its neighboring stations. Based on the received signal strength, it estimates the rates to each neighboring station. Then, when this station needs to transmit an RTs, it uses the pre-estimated rate. If RTS is transmitted successfully, *FAR* follows the strategy in *RBAR* to estimate rate for data frame with the exchange of RTS/CTS. If RTS fails, it is retransmitted at a lower rate.

Received Signal Strength Link Adaptation (**RSSLA**) [5] by Pavon and Choi estimates the channel condition based on the *Received Signal Strength* (RSS). A station monitors all frames it can sense and stores the adapted RSS for each neighboring station. The RSS is adaptively updated with a constant low pass filter coefficient:

$$RSS_n = (1-\alpha) * RSS_{n-1} + \alpha * r \qquad (1)$$

where RSS_n is the *n*th adapted RSS and *r* is the instant RSS retrieved from last received packet. In transmission, the station retrieves the RSS of the destination station and maps it to the corresponding rate.

Taking into account the overhead to sniff all frames in *RSSLA* and the power constraints of mobile IEEE 802.11 nodes, the authors [6] proposed a rate adaptation scheme named *Beacon Assisted Rate Adaptation* (**BARA**). Rather than sense all frames, *BARA* only monitors beacon frames from a base station or a peer station and adapts the RSS of beacon frames with the formula 1. Then the adapted RSS is translated into a rate to transmit the first frame. The rates for other successive frames are directly inferred from the ongoing transmission. Since the beacon frame is mandatory in IEEE 802.11, it is always available. And because it is periodically broadcast, the rate estimated from it should be fairly precise. *BARA* benefits those stations in power saving state because in IEEE 802.11 these stations must periodically wake up to receive the beacon frame.

Theoretically, the modulation scheme is closely associated with SNR [16]. Therefore, the rate should be determined from signal-to-noise ratio measurement. However, recent studies of the signals in realistic environments [4], [17] observe that generally neither SNR nor RSS exhibit a strong correlation with the delivery probability at a given rate. These observations limit the effectiveness of SNR/RSS based schemes in practice.

B. Rate Adaptation Algorithms with Loss Differentiation

A frame loss may be due to channel fading or collision. Without diagnosing the cause of a loss, a rate adaptation scheme is inefficient and wasteful: the rate should be decreased only in response to channel degradation, not for a collision loss. To better respond frame losses, recent rate adaptation research focuses on loss differentiation and loss recovery strategies. This section presents these schemes chronologically.

Pang, Leung and Liew proposed a rate adaptation algorithm called loss-differentiating-ARF (**LD-ARF**) [10] for IEEE 802.11 WLANs by combining *ARF* with a loss-differentiating MAC [18] they developed. *LD-ARF* performs loss differentiation at the receiver. *LD-ARF* assumes there is no hidden terminal problem in a WLAN: all stations can hear each other. *LD-ARF* loss differentiation strategy is based on the following rationale: the frame header is short and thus resilient to wireless channel fading; therefore, if a received frame header can be decoded while the payload can not, this frame corruption is attributed to channel fading. Otherwise, the frame loss is attributed to a collision as Pang *et al.* contend that a collision should destroy both the frame header and body). If the frame loss is due to channel degradation, the receiver issues a negative ACK (*NACK*) that indicates to the source station to lower its rate: the frame source address is assumed to still be available in the frame header. All other operations are the same as in *ARF*.

Strategy *Collision-Aware Rate Adaptation* (**CARA**) [11] by Kim, *et al.* is designed to handle collisions without using RTS/CTS frames under good conditions. *CARA* uses of RTS/CTS in response to a frame loss. When a frame is lost, an RTS precedes the retransmission of the lost data frame. *CARA*'s rationale is that RTS (always sent at the basic rate) is resilient to channel fading. Therefore, if RTS is also lost, the data frame loss is likely due to collision. Except for the use of RTS/CTS, *CARA* adjusts the data rate similarly to *ARF*. Essentially, what *CARA* does is to use RTS/CTS to *reduce* collisions from hidden terminals. To minimize the overhead from the use of RTS/CTS, *CARA* suggests that a transmitting station switches its adapter to sense the channel immediately after a transmission is over. If the channel is sensed busy and the transmission gets lost, this loss is obviously inferred from collision without the need of an RTS. It should be noted that the busy channel sensed at the source station does not necessarily result in collision at the destination station.

Scheme *Robust Rate Adaptation Algorithm* (**RRAA**) [12] by Wong, *et al.* also requires the use of RTS/CTS after a frame loss to eliminate further collisions due to hidden terminals. *RRAA* consists of two elements: rate adaptation (loss ratio estimation and rate selection) and collisions elimination. A station starts transmitting at the maximum rate. *RRAA* measures the loss ratio from recent transmissions statistics over the recent history (or window). In each short cycle (not necessarily equal in time), a window of frames is transmitted at a selected rate. The window size (the number of frames) might vary for different rates. At the end of each window, the frame loss ratio p for the corresponding rate is available for rate adjustment. To select a proper rate for the next window, *RRAA* introduces two thresholds: P_{MTL} and P_{ORI}. If $p > P_{MTL}$, the next lower rate is chosen for the next window transmission. If $p < P_{ORI}$, the rate is increased. If $(P_{ORI} <= p <= P_{MTL})$, the rate remains unchanged and the window slides forward to continuously compute the loss ratio for the current rate. Beyond the rate adaptation, *RRAA* presents a strategy called *Adaptive RTS* (**A-RTS**) to reduce collision losses due to hidden terminals. *A-RTS* maintains a variable RTS_{wnd} which indicates the number of *consecutive* frames to be transmitted with a preceding RTS. RTS_{wnd} is adjusted as follows: when a frame without RTS is lost, RTS_{wnd} is incremented by one with the assumption that this loss is probably due to a collision; when a frame preceded by RTS is lost, or a frame without RTS succeeds, RTS_{wnd} is halved. When integrating the rate adaptation and *A-RTS*, *RRAA* does not include RTS loss into the loss ratio computation. Although *RRAA* turns on RTS to mitigate collision, it does not decrease its rate even if the loss is inferred from channel fading: it adjusts its rate only at the end of the transmission window.

The authors of this paper proposed a rate adaptation scheme *Loss Differentiation Rate Adaptation* (**LDRA**) [13]. *LDRA* attempts to diagnose the cause of a loss and quickly recover. When a frame loss occurs, *LDRA* retransmits the lost frame at the basic rate. If this retransmission at the basic rate succeeds, the loss is attributed to channel fading, otherwise to collision. For channel fading, *LDRA* decreases the rate. The rate remains unchanged for a collision. *LDRA* strategy is analytically justified and particularly efficient in low SNR environments. *LDRA* relies upon the signal-to-noise ratio (SNR) to diagnose losses.

Scheme *Effective Rate Adaptation* (**ERA**) [14] is the latest rate adaptation proposed by the authors of this paper. Based on extensive analysis and evaluation of existing rate adaptation schemes, *ERA* summarizes the effective operations under different channel conditions: channel fading or collisions. *ERA* offers an effective strategy to diagnose losses and to swiftly recover them. To reduce collisions from hidden terminals, *ERA* exploits the fragmentation mechanism in IEEE 802.11 without introducing the overhead of RTS/CTS. *ERA* starts the transmission at an intermediate rate (24 Mbps for IEEE 802.11a/g and 5.5 Mbps for IEEE 802.11b) to quickly converge to the most appropriate rate. In case of frame loss at rate r_{fail}, *ERA* fragments the lost data frame into two fragments: one very short and the remaining. According to IEEE 802.11 standard, if the first fragment gets access to the channel, the channel is reserved for all remained fragments. Thus, by fragmenting, the collision probability for the entire frame is reduced to that of the first (short). For the retransmission, the short fragment is transmitted first at rate r_{fail}. If it succeeds, the loss was most likely due to collision because short frames have higher probability of successful delivery for collisions, but not for channel fading. If the short fragment still fails at rate r_{fail}, it is retransmitted at the basic rate to test for channel fading. If the fragment is successfully transmitted at the basic rate, then the loss is considered from channel fading. Otherwise, it is inferred from collision. After the loss is diagnosed, *ERA* maintains the rate unchanged in case of collision and decreases it for channel fading. To probe potential better channel conditions, *ERA* borrows the concept of adaptive threshold from *AARF* to increase the rate. After $Threshold$ consecutive successful transmissions at a rate r_{old}, the rate is increased to the next higher level r_{new}. However, if the first transmission at r_{new} fails, the channel is inferred to be not robust enough to support the higher rate r_{new}. Then, the rate is reinstated to the prior rate r_{old}. And the $Threshold$ is doubled for the next rate increase. *ERA* fully complies with the IEEE 802.11 and is the first scheme to differentiate loss and reduce collision without using RTS/CTS control frames.

Data rate schemes can be further categorized as *per frame* based or *statistic* based. Per-frame based schemes such as [10], [11], [13], [14] quickly react to channel variations while statistic based schemes [12] are slower but yield better long term performance.

C. Characteristic Summary of Rate Adaptation Schemes

Based on the above detailed description of these rate adaptation schemes [1]–[14], Table I summarizes their characteris-

Scheme	Loss Differentiation	Based Location	Condition Indicator
ARF	No	Sender Based	Loss ratio
AARF	No	Sender Based	Loss ratio
Onoe	No	Sender Based	Loss ratio
SampleRate	No	Sender Based	Loss ratio
RBAR	No	Receiver Based	SNR
OAR	No	Receiver Based	SNR
FAR	No	Hybrid	SNR
RSSLA	No	Sender Based	RSS
BARA	No	Sender Based	SNR
LD-ARF	Yes	Receiver Based	Loss ratio
CARA	Yes	Sender Based	Loss ratio
RRAA	Yes	Sender Based	Loss ratio
LDRA	Yes	Sender Based	SNR
ERA	Yes	Sender Based	Loss ratio

TABLE I
CHARACTERISTICS OF RATE ADAPTATION SCHEMES

tics.

III. PERFORMANCE EVALUATION

Due to space limitations, this section presents preliminary but fairly representative performance evaluations of three rate adaptation schemes using the *ns-2* network simulator. Additional results are presented in a technical report [14].

A. Simulation Configuration

Experiments were carried out with IEEE 802.11g MAC on simulator *ns-2* [19]. The physical layer parameters refer to the Cisco Aironet 802.11a/b/g cardBus wireless LAN adapter [20]. Schemes *ARF*, *CARA* and *ERA* were chosen and implemented for comparison: *ARF* from the category without loss differentiation; *CARA* from the category with loss differentiation but requiring RTS/CTS; and *ERA* from the category with loss differentiation but without requiring RTS/CTS. The performance of these schemes is evaluated in two cases: a static mesh network environment and a mobile network. A set of experiments evaluated the impact of congestion level while another set evaluated the performance in a collision free environment. Most simulations were conducted with multiple wireless nodes. The *static* network topology of 16 client stations and one access point is shown in Figure 2. These stations are within the radio coverage of the access point, but they do not necessarily *hear* each other. Therefore the existence of hidden terminal depends on the network area size. To simulate a realistic environment, wireless channel fading is simulated with Ricean fading model [16] that takes into account both distance fading and time varying channel fluctuations. Consequently, such a simulation environment contains mixed losses from both channel fading and collisions. Another simulation scenario was carried out with one client and two-ray channel fading model.

B. Throughput on a Static Mesh Network

In this experiment, the network area size in Figure 2 is varied to adjust the congestion level. All client stations transmit constant bit rate (CBR) UDP traffic with packets of one Kbyte to the access point. Figure 3 plots on the y-axis the throughput improvement by percentage achieved by *CARA* over *ARF*, and *ERA* over *CARA* respectively. As we observe, *ERA* performs best in heavily congested environments due to its accurate loss differentiation and effective recovery strategy. *CARA* outperforms *ARF* with its ability to suppress collision loss in a congested environment.

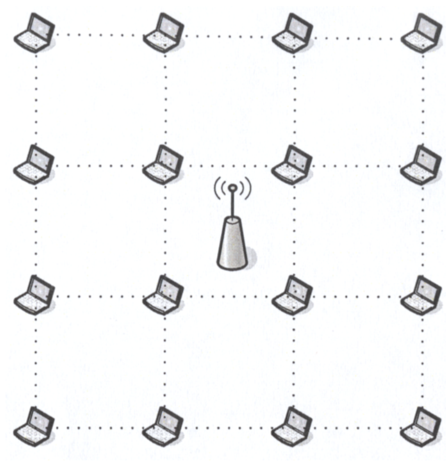

Fig. 2. Topology of 17 static stations

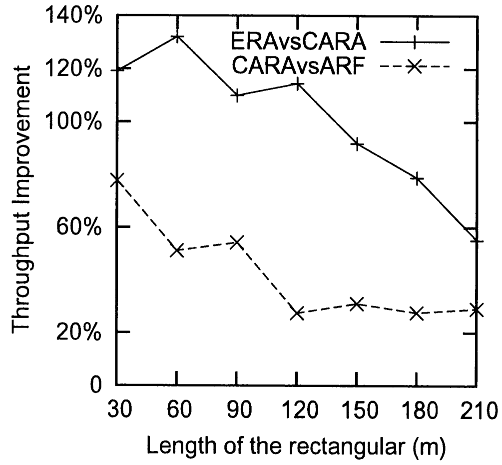

Fig. 3. Throughput improvement under static mixed environment

C. Thoughput for Mobile Network

In this simulation, all 16 client stations are *mobile* with random velocities (from 2 m/s to 30 m/s) to random destinations with a short pause (1 s) between consecutive movements in a 350m×350m area. The access point is statically located at the center of the network. All stations keep transmitting CBR traffic to the access point.

This experiment evaluates the throughput performance of these schemes with *different* traffic packet lengths: 500 bytes, 1000 bytes and 1500 bytes. Figure 4 depicts the simulation results for *ARF*, *CARA*, and *ERA*. The horizontal axis represents the packet length used for each run. The vertical axis represents the throughput improvement. With longer frames, the collision probability is larger; therefore *ERA* has more opportunities to exploit its strengths over *ARF* and *CARA*. As expected, *CARA* displays its ability to alleviate collisions with more improvement over *ARF* in the case of longer frames.

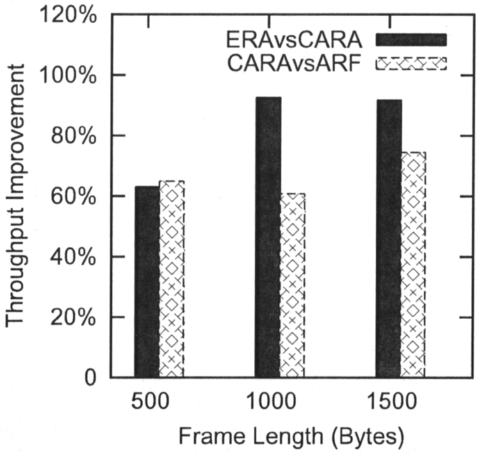

Fig. 4. Throughput improvement under mobile environment

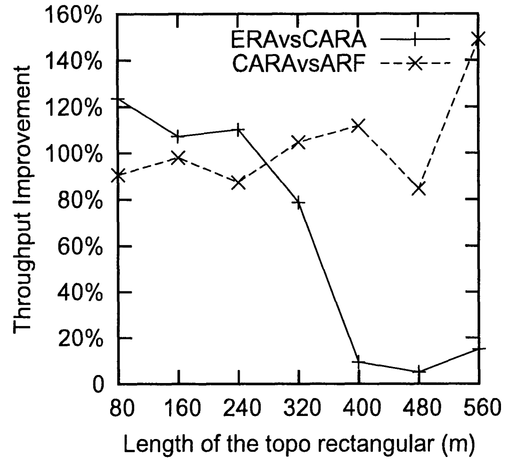

Fig. 5. Throughput under different levels of collision

D. At Different Congestion Levels

This section presents the performance of *ARF*, *CARA*, and *ERA* at different congestion levels. We vary the degree of congestion by changing the size of the network area as shown in Figure 2. The network is static. Figure 5 plots on the y-axis the throughput gains of *ERA* over *CARA*, and *CARA* over *ARF*, respectively. The x-axis represents the length of the network area. The CBR UDP traffic packet size is set to 1000 bytes.

ERA performs best followed by *CARA*. Especially, as collisions increase (smaller network area), more improvement is achieved by *ERA* due to its more accurate loss differentiation and its efficient recovery strategy. *CARA* outperforms *ARF* when the area becomes larger with more hidden terminal instances. In case of hidden terminals, *CARA* takes advantage of RTS/CTS to eliminate collisions.

E. Stable Channel Conditions Without Collision

We simulate a fixed station and one access point to emulate the scenario where only one wireless laptop is used in a home for example. The two-ray ground fading model is used in this simulation to ensure that some constant rate is guaranteed (with no losses) at a given location: the highest guaranteed rate under a two-ray ground fading model depends only on

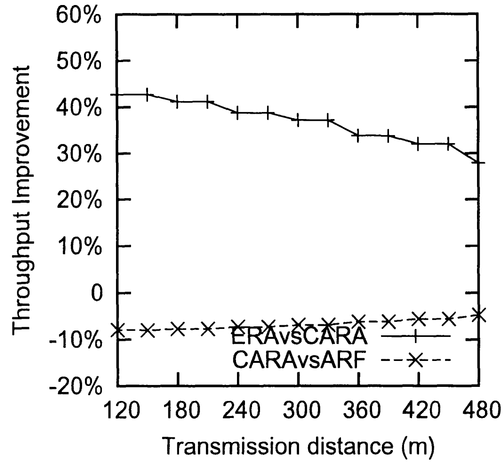

Fig. 6. Throughput under stable channel conditions

distance. The two curves in Figure 6 plot the throughput gain of *ERA* over *CARA*, and *CARA* over *ARF* respectively when the client is at some constant distance (x-axis) from the access point. *ERA* outperforms *ARF* and *CARA* due to 1) its effective recovery strategy and 2) the mechanism borrowed from *AARF* (adaptively adjust the threshold number ($Threshold$) of consecutive successful transmissions required to increase the rate). The reader can observe that *CARA* performs worse than *ARF* under these conditions because *CARA* wastes time in sending RTS/CTS to eliminate inexistent collisions.

In all the above simulations, the schemes with loss differentiation and collision elimination outperform the simple schemes in collision dominated environments. Effective loss differentiation and recovery strategies (e.g., *ERA*) improve network performance.

IV. Open Issues in Rate Adaptation for IEEE 802.11 Networks

Since the earliest rate adaptation work *ARF* for IEEE 802.11 networks, rate adaptation has been extensively studied in the last decade. However, as shown by Reis *et al.* [21] with measurement from realistic scenarios, the transmission of new data only accounts for up to 40% of the time: most of the remaining time is consumed by retransmissions. Therefore, rate adaptation requires more efforts to improve network utilization.

- *Limited measurement from realistic scenarios*: Measurements from realistic environments are scarce: the measurements in [4], [12], [17], [21] present partial observations with the experiment settings limited to a specific testbed. More results from representative environments, especially from public sites, are needed to better understand the traffic and the channel model. Such measurements constitute the base for good rate adaptation schemes.
- *No performance comparison*: With so many existing rate adaptation schemes, there is no work that systematically compares them within the same settings and/or conditions. The performance evaluation in realistic environ-

ments can provide insights to the design of better rate adaptation schemes.
- *New rate adaptation scheme*: So far, there is yet no rate adaptation scheme that is 1) effective in both channel fading and collisions dominated environments, and 2) responsive to quick transient channel dynamics, and yielding long term performance. New rate adaptation schemes are needed.

V. Conclusion

This paper presents in detail rate adaptation schemes proposed for IEEE 802.11 networks. First generation schemes do not differentiate the cause of a loss and yield low performance in collision dominated environments. Second generation schemes diagnose the cause of a frame loss. These recent schemes differ in their strategies to measure the current quality of a channel and to recover from losses. This paper highlights their key characteristics and common features. Performance of representative schemes is compared with simulations. In general, *ERA* outperforms two representative schemes *ARF* and *CARA*. However, *ERA* still needs more development to make it effective under most network and traffic conditions.

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