BEWARE: Background Traffic-Aware Rate Adaptation for IEEE 802.11 MAC

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***Abstract*— IEEE 802.11-based devices employ rate adaptation algorithms to dynamically switch data rates to accommodate the fluctuating wireless channel conditions. Many studies observed that, when there are other stations transmitting in the network, existing rate adaptation performance degrades significantly due to the inability of differentiating losses between wireless noise and contention collisions. They proposed to exploit optional RTS frames to isolate the wireless losses from collision losses, and thus improve rate adaptation performance. In this paper, we conduct a systematic evaluation on the effectiveness of various existing rate adaptation algorithms and related proposals for loss differentiations, with multiple stations transmitting background traffic in the network. Our main contributions are two-fold. Firstly, we observe that most existing rate adaptations do not perform well in background traffic scenarios. In addition, our study reveals that RTS-based loss differentiation schemes can mislead the rate adaptation algorithms to persist on using similar data rate combinations regardless of background traffic level, thus result in performance penalty in certain scenarios. The fundamental challenge is that rate adaptation must dynamically adjust the rate selection decision objectives with respect to different background traffic levels. Secondly, we design a new Background traffic aware rate adaptation algorithm (BEWARE) that addresses the above challenge. BEWARE uses a mathematical model to calculate on-the-fly the expected packet transmission time based on current wireless channel and background traffic conditions. Our simulation results show that BEWARE outperforms other rate adaptation algorithms without RTS loss differentiation by up to 250% and with RTS by up to 25% in throughput.**

Keywords- Rate adaptation, 802.11, MAC

I. INTRODUCTION

With the large-scale deployments of wireless local area networks (WLANs) in homes, offices, and public areas, the IEEE 802.11 standard has become the dominant technology in providing low-cost high-bandwidth wireless connections. A large part of the success of WLANs can be attributed to the implementation of several simple yet fully distributed algorithms in dealing with the fundamental challenges for wireless communications, including transmissions on a shared medium and lossy wireless channel conditions. For example, the Distributed Coordination Function (DCF), a Carrier-Sensed Multiple Access with Collision Avoidance (CSMA/CA) based Medium Access Control (MAC), mandates the stations to first check if the medium is idle before transmit packet. The Collision Avoidance mechanism further regulates stations to backoff for a random amount of time before transmission attempts, such that the chance of collisions is probabilistically low [1]. In addition, enabled by different levels of complexity and redundancy in signal modulation and coding schemes, the IEEE 802.11 standard employs multiple data rates to combat the volatile nature of wireless channel. IEEE 802.11-based stations implement rate adaptation algorithm (RAA) to dynamically select the best transmission rate that yields the highest performance in any given wireless channel conditions.

The key challenges are that RAA must not only accurately estimate the channel condition in order to infer the most suitable data rate, but also be very responsive to the rapidly fluctuating wireless channel dynamics. Several approaches have been proposed [2]-[9], including the use of received signal strength, local Acks, and packet statistics to design a RAA that addresses the above challenges. The effectiveness of RAAs has been extensively evaluated under various wireless channel conditions, when there is only one station in the network. On the other hand, in multiple-user environment, several studies [10][11] reported that some types of RAAs' performance, e.g. Automatic Rate Fallback (ARF)[2], can degrade drastically. It is because, as ARF lowers its data rate whenever consecutive frame losses occur, collision losses introduced by contention-based IEEE-802.11 DCF can mislead ARF to think the wireless channel has deteriorated causing it to unnecessarily lower its rate and resulting in performance degradation.

Based on this observation, there have been a few attempts to aid rate adaptation algorithms in dealing with the collision effect. The key idea is to provide RAAs the ability to differentiate between wireless losses and collision losses such that RAAs can resume their normal functionality by filtering only wireless losses into rate decision process. On the one hand, [11] suggests exploiting the Request-To-Send/Clear-To-Send (RTS/CTS) exchange to differentiate collision and channel errors. With RTS/CTS exchanges preceding data transmissions, the RAAs are no longer affected by the collision effect by assuming the only cause for the data frame transmission failure after a successful RTS/CTS exchange is due to channel error not collision. CARA [10] further proposes to selectively turn on RTS/CTS in order to save the extra RTS/CTS overhead. On the other hand, without RTS/CTS frames, [11][12] add extra frames and fields to explicitly notify the sending station whether the transmission failure is due to collision or channel errors.

While these proposals provide significant improvements compared to RAAs without loss differentiation capability, it is unclear whether loss differentiation is good enough to deal with all kinds of mixed wireless and collision loss scenarios. The fundamental problem is, as we will show later in this paper, that *background traffic from other contending stations changes the throughput ranking of the operating data rates*. In other words, under the same wireless condition, the data rate yields the highest throughput in no background traffic scenarios is not necessarily the best one in background traffic scenarios. As loss differentiation schemes filter out all collision losses for RAA, the RAAs become insensitive to the throughput ranking changes caused jointly by wireless losses and collision losses, causing performance degradation.

In this paper, we design a new Background traffic aware Rate Adaptation Algorithm (BEWARE) that explicitly addresses the mixed effects from wireless and collision losses. Our contributions of this paper are: ***i.*** we systematically evaluate the performance of RTS-based loss differentiation in different mixed wireless and collision losses scenarios. We identify when and why RTS loss differentiation does not work in certain scenarios, ***ii.*** we use the insight in these systematic evaluations to identify a key parameter – *the expected packet transmission time* – to explicitly address the mixed effects from wireless and collision losses on all available data rates. We propose an online algorithm to estimate this parameter of all data rates and embed this information into the RAA design as the key rate decision maker, and ***iii.*** we compare the performance of BEWARE with other RAAs with and without loss differentiation, and observe up to 250% and 25% performance improvement, respectively.

The rest of the paper is organized as follows. Section II reviews the existing RAAs and related loss differentiation approaches. Section III evaluates the performance of existing RAAs and loss differentiation schemes. Section IV presents the design of our background traffic aware rate adaptation algorithm, and Section V evaluates its performance under various background traffic scenarios. Section VI concludes.

II. RELATED WORK

In this section, we briefly review the existing rate adaptation algorithms (RAAs) and related loss differentiation schemes that help RAAs deal with collisions in multiple-user environment. We discuss pros and cons of each approach.

A. Existing Rate Adaptation Algorithms

As the 802.11 standard intentionally leaves the rate adaptation algorithms open to vendors' implementation, there have been quite a few RAAs proposed by academia and industry. They can be broadly classified into three categories based on the information they collect for rate selection decisions: 1) statistics based RAAs, 2) received signal strength (RSS) based RAAs, and 3) hybrid RAAs.

1) Statistics-based rate adaptation algorithms

Statistics-based RAAs collects frame transmission statistics such as number of retries, number of frame success and failures. These statistics are further processed and compared for different rates or pre-set thresholds to infer for current wireless channel conditions. Based on the statistics the RAA uses for rate decisions, we can further categorize this class of RAAs into three different approaches. i) *Retry-based rate adaptation*: This approach [2][3] uses number of transmission successes/losses as the indicator of good/bad wireless condition, and increase/decrease data rate accordingly. For example, ARF [2] decreases the data rate upon two consecutive transmission losses and increases data rate after ten consecutive transmission successes. However, despite its easy design, previous study [5] has shown that, due to randomness of the wireless loss behavior, there is very weak correlation between past consecutive transmission successes/losses and future channel condition, and consequently this approach tends to yield pessimistic rate estimations. ii) *Frame-Error-Rate(FER)-based rate adaptation*: this approach [4][5] calculates FER by the ratio of the number of received ACK frames to the number of transmitted frames. The RAA decreases and increases the operation data rate if FER exceeds some pre-determined thresholds. The major drawback is the pre-determined FER thresholds. As wireless channels are so vulnerable to many factors such as multipath, channel fading, and obstructions, it is difficult for one set of pre-determined FER thresholds to fit in all circumstances. iii) *Throughput-based rate adaptation*: This approach [6] calculates each data-rate's throughput based on the packet length, bit-rate, and the number of retries collected during a predefined decision window (~1 sec). The major drawback of this approach is the excessive length of the decision window. As the decision window has to be large enough to collect meaningful statistics, it causes the rate adaptation algorithm to be less responsive to sudden wireless condition changes.

2) Signal-strength-based rate adaptation algorithms

This class of RAAs [7][8] relies on wireless signal strength information, such as Received Signal Strength Indicator (RSSI) or Signal-to-Noise Ratio (SNR), to make the rate adjustment decisions. They assume a strong correlation between received signal information and the delivery probability of a data rate. The RAAs pick the data rate based on a pre-determined mapping between the received signal strength and throughput. Meanwhile, there are two approaches to overcome the communication issue of piggybacking the signal strength measurement taken at the receiver side to sender so that sender can adjust the data rate accordingly. One has to either use explicit signaling [8], which is incompatible to the IEEE 802.11 standard, or assume the channel is symmetry [7], which is clearly not the case in real-world scenarios, and thus of little practical value.

In addition, this class of RAAs suffers from other drawbacks. Firstly, the rate adjustment mechanism requires a priori channel model to map the received signal information to corresponding data rate throughput. In reality, such mapping is highly variable and a model established before-hand may not be applicable to any environments later.

Secondly, it is not trivial to obtain reliable signal strength estimation from the radio interfaces.

3) *Hybrid rate adaptation algorithms.*

The hybrid RAA [9] collects both frame transmission statistics and received signal strength, and use statistics-based controller as the core rate adaptation engine. The rate decision can be overridden by signal strength based controller if it detects a sudden changes in received wireless signal strength. As hybrid RAA design still assumes symmetric wireless channel and pre-established RSSI-to-rate thresholds, this approach is not immune from the drawbacks we discussed in signal-strength-based RAAs section.

In summary, all types of RAAs strive to obtain accurate channel estimations from different kinds of loss characteristics and decide *when to decrease* and *when to increase* the rate. However, in multiple-user environment, packet collisions incur new sources of frame losses. None of these RAAs explicitly address this issue. In the next section, we review several proposals that try to aid RAAs in dealing with collision effects.

B. *Loss differentiation for rate adaptation*

Previous studies reported that ARF's performance degrades drastically when operating with mixed frame losses from wireless noise and contention collisions. Because ARF treats collision losses no different than wireless losses, ARF excessively decreases its rate upon contention collisions, even when wireless channel is close to perfect. This "rate poisoning" effect results in severe performance degradation. There have been two approaches to aid rate adaptation algorithms in differentiating wireless losses from collision losses. i) *Loss differentiation by RTS/CTS*: [10] and [11] suggest to exploit the RTS/CTS exchange to differentiate collision and channel errors. With RTS/CTS exchanges preceding data transmissions, RTS-based loss differentiation assumes the only cause for the data frame transmission failure after a successful RTS/CTS exchange is due to channel error not collision. Therefore, RAA rate decision process reacts only on wireless losses filtered by RTS/CTS, and RAAs are no longer affected by the collision effect. Kim et al. propose Collision-Aware Rate Adaptation (CARA), to reduce the extra RTS/CTS overhead by selectively turning on RTS/CTS after data frame transmissions fail at least once without RTS/CTS. ii) *Loss differentiation by explicit notification*: [11] and [12] propose to add extra frames and fields to explicitly notify the sending station of the source of losses. However, both proposals require changes to the IEEE 802.11 standard and are not compatible with existing 802.11 compliant devices, thus they are not favorable for real-world deployments.

In summary, loss differentiation is the dominating approach for RAAs dealing with collision effects when there are other stations transmitting traffic in the network. However, it is not clear whether loss differentiation is sufficient to guide RAAs to perform well in various multiple-user environments with mixed wireless and contention conditions. As we will show later in the paper, while RTS-based loss differentiation works in certain circumstances, we also found other scenarios that RTS-based loss differentiation performs poorly, especially when it operates independently with other RAAs or fixed rate background traffic.

III. PERFORMANCE OF RATE ADAPTATION ALGORITHMS WITH BACKGROUND TRAFFIC

In this section, we first explain briefly how IEEE 802.11 rate adaptation works. In particular, we analyze how rate selection objective varies with the level of background traffic. Furthermore, we systematically evaluate the performance of various RAAs with RTS loss differentiation schemes under different scenarios, including varying number of stations in the network and the distance between stations and access point. As we will show in this section, it is critical to examine how and why these RAAs do not perform well with background traffic. By such an investigation, we not only better understand the necessity for a RAA that does take background traffic into consideration, but also gain insight into how to design such a RAA.

A. *IEEE 802.11 Rate Adaptation and Background Traffic*

To visualize the throughput-distance tradeoff among multiple data rates employed by IEEE 802.11 standard, in Fig. 1, we use ns-2 [20] to simulate an 802.11a station's maximum throughput as it moves away from the access point (AP) in Ricean fading environment [13][1]. As seen in Fig. 1, among the 8 data rates available in IEEE 802.11a, higher data rates can achieve higher throughput, but their transmission ranges are shorter. The crossing points of two adjacent data rates indicate that, at a given location, the error rate of the high data rate is becoming too high that it's actually more favorable to use the next lower data rate to benefit from the lower error rate. Clearly, rate adaptation mechanism should try to follow such transitions as close as possible to select the best data rate according to the current wireless channel condition experienced by the link. Ideally, if a rate adaptation mechanism has perfect knowledge of the current network condition, its data rate selections follow closely with the outer envelope (plotted as thick solid line) of Fig 1. In this way, the throughput yielded by the rate adaptation mechanism is always maximized given a particular channel condition. We will refer to this outer envelope concept as the "*best-available strategy*" and its performance as *maximum throughput* throughout the paper.

On the other hand, Fig. 2 plots the performance of the same data rate set under the same wireless channel condition, but with 12 other stations transmitting saturated background traffic in the network. Note that, not only the shape of staircase like throughput-distance curves changes, but the rates selected by the best available strategy also change for the same location. It is because the data frames transmitted by any data rate are subject to not only wireless losses but also collision losses caused by medium contentions with other stations. In other words, the extra backoff time spent in medium contentions and collisions change the crossing points of two adjacent data rates, and thus the rate switching strategy. This combined effect changes the performance ranking of data rates for a given location. Fig. 3 further

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[1] Refer to Sec. 5.1 for detailed simulation parameters

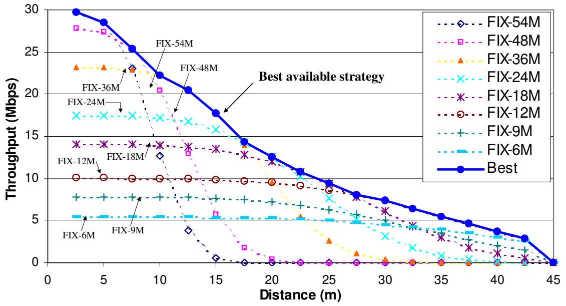

Figure 1. Throughput versus distance for IEEE 802.11a data rates, no background traffic

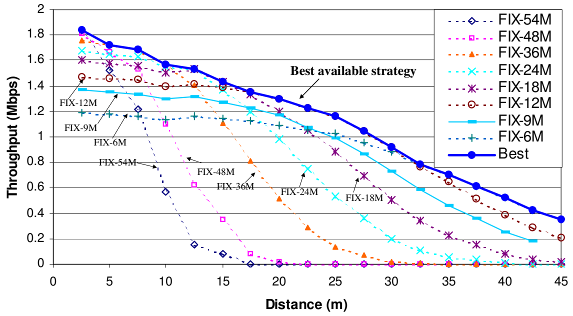

Figure 2. Throughput versus distance for IEEE 802.11a data rates, with 12 background traffic stations

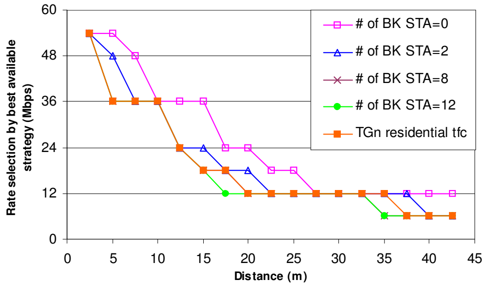

Figure 3. Best available data rate under different background traffic scenarios

illustrates this effect by plotting the rate selections by best available strategy when operating with different number of saturated background traffic stations and unsaturated residential traffic benchmark scenario as specified in [14]. As we can see from Fig 3, the rate selected by best available strategy varies widely with background traffic intensity. In other words, the rate adaptation strategy that works well in one background traffic scenario may not work in other background traffic scenario, hence the rate adaptation mechanism needs to explicitly address this phenomenon.

Previous study [15] identified that the core of RAAs is on "when to decrease" and "when to increase" the transmission rate. Here, we argue that the rate selection objectives in terms of "*where to decrease/increase to*", which change with background traffic intensity, are essential to RAA design in multi-user environment. ***It is very critical for rate adaptation designs to be aware of such changes and adjust its rate selection strategy to accommodate such changes; otherwise it will suffer from serious performance degradation***.

B. Performance of RAAs in RTS Access Mode

Previous studies identified that the lack of ability in differentiating between wireless losses and collision losses is the main problem for ARF to suffer from rate poisoning in background traffic scenarios. They reported the superior performance of ARF with RTS on over that with RTS off. However, those studies did not provide systematic investigation into whether RAA with RTS really achieves the optimal throughput and why it does or does not. Besides, we convey detailed comparisons among different RAAs with RTS on, which are also not offered by previous studies. We include representable RAAs from all three classes of statistics-based RAAs, i.e., ARF, ONOE [16], Sample-Rate (SMPL) [6], and RRAA-basic [5], in addition to signal strength based RBAR [8].

With the same simulation settings in the previous section, we first place all stations at 2.5m away from the access point and turn on RTS for all stations. We isolate the effects of RTS loss differentiation in performance comparisons by enabling only one station with RAA on, and other background traffic stations with fixed data rate. When there is little wireless loss for the RAA-enabled station, we observe from Fig 4 that all RAAs perform almost the same as the best available strategy, regardless of how many stations transmitting background traffic in the network. We then move the RAA-enabled station to 12.5m away from the access point, we can see from Fig 5 that RAAs start to lose track from the best available rate and even drop their throughput lower than that is offered by the lowest data rate. To further explain such scenario, we plot Fig 6 to illustrate rate selection breakdowns of ARF, as an example, as distance to access point increases. We can see that the rate selection of ARF remains almost the same as number of background traffic stations increases. This is because RTS isolates the wireless losses from collision losses. As a result, RAA makes the rate decisions solely on wireless losses, and RAAs become insensitive to the throughput ranking changes, which are illustrated as the dotted lines in Fig 6, caused jointly by wireless losses and collision losses.

We further examine the rate selection of all statistics-based RAAs with RTS-on, and find the same phenomenon exists. It follows that ***turning on RTS misleads RAAs into using rates only suitable for no-background-traffic in scenarios with background traffic, where these rates are not always suitable.*** As a result, RTS loss differentiation only works well when the rate selections are similar for all other background traffic scenarios. On the other hand, since SNR-based RBAR makes rate decisions by signal strength, the data rate selected by RBAR is always the same regardless background traffic intensity. In other words, although the exact cause of bad rate selections is different, RBAR also performs badly in background traffic scenarios.

C. Performance of Collision-Aware Rate Adaptation (CARA)

Kim et. al.[10] propose to adaptively turn on RTS-CTS exchanges to reduce the extra overhead introduced by RTS loss differentiation. The mechanism, as called CARA1 in [10], works in the following manner. By default, the data

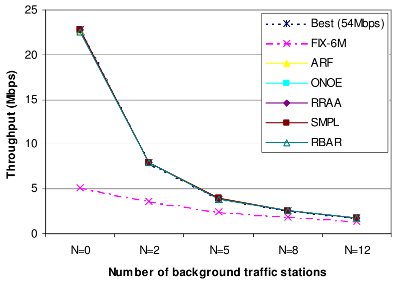

Figure 4. Throughput comparison for RAA-enabled station with RTS loss differentiation at 2.5m away from access point, with various number of background traffic stations in RTS access mode

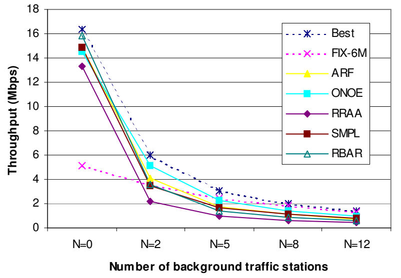

Figure 5. Throughput comparison for RAA-enabled station with RTS loss differentiation at 12.5m away from access point, with various number of background traffic stations in RTS access mode

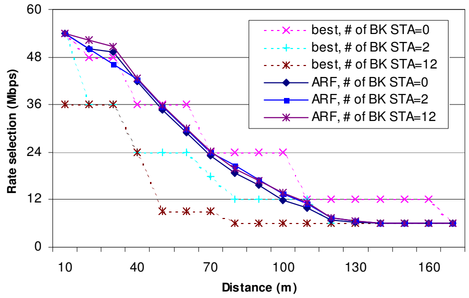

Figure 6. Data rate selection for ARF with RTS/CTS and Best available strategy, with various number of background traffic stations in RTS access mode

frames are transmitted without RTS. When the consecutive failure count reaches probe activation threshold (P_{th}), the RTS-CTS exchange is activated. If the *consecutive* failure count further reaches consecutive failure threshold (N_{th}), the transmission data rate is decreased. The default values of P_{th} and N_{th} are set as 1 and 2 in [10], respectively. The data rate is increased as the consecutive success count reaches 10, similar to ARF.[2]

In this section, we compare the performance of CARA with ARF in basic access mode and the best available strategy. As shown in Fig. 7, we vary the distance between the RAA-enabled *station* and access point from 2.5m~45m, and show the RAA station throughput when operating with 12 other stations transmitting background traffic at fixed 54Mbps data rate. We can see that, deviate from what reported in [10], CARA does not always offer superior performance over rate-poisoned ARF. In particular, when the station is far away from AP (>25m), the most suitable rates turn to be lower rates. In these cases, CARA's adaptive RTS/CTS mechanism only adds overhead to packet transmissions, and no longer functions as loss differentiator for underlying RAA. On the other hand, when CARA does outperform ARF, its performance is 15%~25% less than the best available strategy. *It follows that, while **RTS-based loss differentiation schemes help RAAs distinguish between wireless and collision losses in some scenarios, they do not perform well in some other scenarios.***

In summary, by systematic evaluations on how different RAAs perform with different operating modes in mixed wireless and collision environment, we made the following observations and conclusions: *i) The best available strategy varies significantly with the level of background traffic. We argue that any rate adaptation mechanism should be aware of such change at the presence of background traffic, or it will suffer from serious performance degradation. ii) We show that none of the existing RAAs we investigated perform well in every background traffic scenario. iii) We see that, even with RTS loss differentiation or CARA, there are also situations where these mechanisms perform poorly. In fact, in those cases, RTS loss differentiation or CARA hurt the performance.* With these valuable observations, we present a new background traffic aware RAA design in the next section.

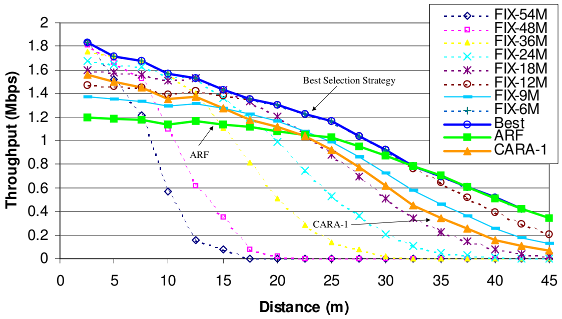

Figure 7. Throughput comparison for ARF, CARA1, and Best (best available strategy) with 12 background traffic stations in basic access mode

IV. *BEWARE* DESIGN

From the lessons we learn from previous section, we know that the key for RAA algorithm to perform well in background traffic scenarios is to incorporate not only wireless channel statistics but also background traffic condition as indicators in accessing the effectiveness of each available data rate. As a result, in this section, we present the design of BEWARE, a Background traffic aWaAre RatE adaptation algorithm for IEEE 802.11-based MAC. The center part to this design is to use a mathematical model to calculate the expected packet transmission time of each data rate that attributes the combined costs of wireless channel errors and background traffic contentions as we discussed in Sec. 3. The rate selection engine then uses this metric to find the data rate that yields the highest throughput in the given wireless channel and background traffic condition. The goals to design such rate selection strategy are two-fold: it has to be robust against any degree of background traffic; meanwhile, it is also responsive to random and even drastic wireless channel changes.

Although using the *expected-packet-transmission-time* as rate selection metric may seem at first as straightforward, it became clear only after our thorough and systematic investigations (in the previous section) on how and why various existing RAAs do not perform well with background traffic. In addition, this concept is novel as no existing studies, to the best of our knowledge, have used such a rigorous metric in RAA design. Next, we describe the

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[2] We do not consider the optional Channel Collision Assessment (CCA) detection, which is called CARA-2 in [10], as CARA-2 only provides marginal performance gain over CARA-1

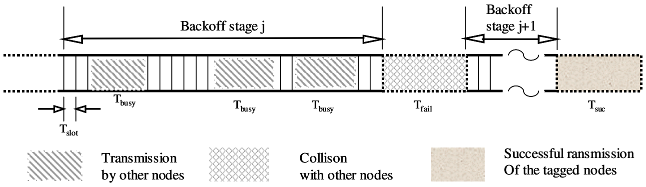


Figure 8. Packet transmission and collision events during IEEE 802.11 MAC backoff

mathematical model for expected packet transmission time calculations in Sec. 4.1, then the rate selection engine in Sec. 4.2.

A. Packet transmission time estimation

The core of BEWARE design is the estimation for expected packet transmission time of each data rate, with the consideration of mixed effects from wireless channel condition and collisions. In CSMA/CA-based 802.11 MAC, the overall time duration required to complete a packet transmission starts from the instant that a packet becomes the head of the transmission queue and MAC layer starts contention backoff process, to the instant that the packet completes the backoff process by being either successfully received or dropped because of maximum retry limit has reached. Therefore, as shown in Fig. 8, we calculate expected packet transmission time by carefully analyzing the duration and occurring probability of different events take place at backoff stages, as follows.

a) When the backoff timer decrements, the time slot is either sensed as idle (for T_{slot}, the length of one time slot) or as busy occupied by background traffic transmission (for T_{busy}, the average medium occupation time used by background traffic transmissions). We define P_{busy} be the probability that, at a given time slot, the backoff timer is frozen due to busy medium in carrier sensing. It follows that the occurring probability of idle slot and busy slot is (1- P_{busy}) and P_{busy}, respectively.

b) When the backoff timer expires (i.e. decrements to zero), the attempt of packet transmission either fails (after T_{fail}) or succeeds (after T_{succ}). We define P_{fail} to be the frame error probability. It follows that the occurring probability of packet failure and success is P_{fail} and (1- P_{fail}), respectively.

For the parameters required to model the above process, we acquire all except T_{slot}, which is specified in different version of IEEE 802.11 standard, directly from monitoring channel activity. Specifically, we determine P_{fail} by counting the ratio of failed packet transmission attempts and total packet transmission attempts. We also obtain P_{busy} and T_{busy} by keeping track of the number and duration of experienced collisions, respectively. On the other hand, T_{fail} and T_{succ} are directly determined by the operating data rate. Note that, in practice, it may be difficult to obtain some of these parameters accurately due to implementation complexity in real devices. We can consider alternative approaches[17][18] by using number of consecutive idle slots between two busy slots to estimate P_{busy} and P_{fail}.

Once these parameters are collected, we can construct a mathematical model calculating the occurring probability for combinations of all different backoff events throughout all backoff stages. We first define the occurring probability $F_{k,n-k}^{j}$ that, in any single backoff stage j with backoff timer selected from 0 to W_j (maximum number of backoff slots in stage j), there are exactly k busy time slots and (n-k) idle slots is,

$$F_{k,n-k}^{j} = \frac{1}{W_j} C_k^{i+k} P_{busy}{}^{k} (1-P_{busy})^{n-k} \quad , \quad 0 \le k \le n \le W_j. \qquad (1)$$

Moreover, we know that any combination of number of busy and idle slots can be a cumulative effect from successive backoff stages. Therefore, we then define $S_{k,n-k}^{j}$ for probability of backoff counter being frozen (k-j) times and idle (n-k) times that up to back off stage j (which implies packet transmission failed j times),

$$S_{k,n-k}^{0} = F_{k,n-k}^{0}, \quad 0 \le k \le n \le W_0 \quad , for \quad j = 0.$$

$$S_{k,n-k}^{j} = P_{fail} \sum_{m=0}^{k-1} \left(\sum_{i=0}^{n-k} S_{m,i}^{j-1} \times F_{k-j-m,n-k-i}^{j} \right) \qquad (2)$$

$$, for \quad 1 \le j \le m, \quad j \le k \le n \le \sum_{i=0}^{j} W_i - 1.$$

, where m is the number of backoff stages specified in the standard.

For stage 0, this term equals Equation 1. For stage greater than zero (i.e. j=1,2,…,m), this term includes all possible cases, from combination of previous stage(s) to the current stage, which result in (n-k) idle slots, (k-j) busy slots, and j failed transmission periods. In other words, the packet transmission time when such combination happens can be characterized by,

$$T_{k,n-k}^{j} = (k-j) * T_{busy} + j * T_{fail} + (n-k) * T_{slot} + T_{succ}. \qquad (3)$$

We then use an intermediate term to consolidate the effects from different backoff stages,

$$T_{k,n-k} = (1-P_{fail}) * \sum_{j=0}^{m-2} (S_{k,n-k}^{j} * T_{k,n-k}^{j}) + S_{k,n-k}^{m-1} * T_{k,n-k}^{m-1}. \qquad (4)$$

As a result, the expected packet transmission time are derived as,

$$T_{avg} = \sum_{k=0}^{N} \sum_{n=k}^{N} T_{k,n-k}, \qquad where \quad N = \sum_{i=0}^{m-1} (W_i - 1). \qquad (5)$$

Once the expected packet transmission time is obtained, it is sent to the rate selection module for rate selection decisions. While the accuracy of this model has been evaluated in our previous work [19], as we will show in the next section, such model can be very useful when integrated into a RAA design in estimating the efficacy of data rates.

As we can see from the derivation in this section, average packet transmission time is a function of several parameters from the environment, i.e. P_{busy} P_{fail}, and T_{busy}. In the presence of background traffic, these parameters should all

TABLE I. THE TURNING POINT TO SWITCH FROM 36MBPS TO 24MBPS IN DIFFERENT BACKGROUND TRAFFIC CONDITIONS

	P_{busy}	T_{busy}(ms)	P_{fail}^{36}
No background traffic	0	0	0.24
Background traffic scenario #1	0.1	0.25	0.14
Background traffic scenario #2	0.2	0.25	0.1
Background traffic scenario #3	0.1	0.5	0.105
Background traffic scenario #4	0.2	0.5	0.07

be considered when making rate selection decisions, as opposed to concentrate on just wireless losses or the differentiation of wireless losses and collision losses as it is believed in previous studies. We further illustrate this point by the following example. Consider two adjacent data rates, 36Mbps and 24Mbps, available in IEEE 802.11a standard. When switching from the higher rate to the lower rate, we expect a turning point that the frame error rate change from P_{fail}^{36} to P_{fail}^{24} , resulting in $T_{avg}^{24} < T_{avg}^{36}$. For the ease of discussion, let us assume P_{fail}^{24} =0 for a given wireless environment, and the rate selection algorithm search for the right turning point P_{fail}^{36} to switch from 36Mbps to 24Mbps. Table I lists the turning point in different background traffic conditions.

As we can see from Table I, the turning points of background traffic scenarios differ significantly from that of no background traffic scenario. The turning point shifts toward less lossy environment (smaller packet error rate) when background traffic level, P_{busy} and T_{busy}, increases. This observation has an implication in RAA's performance: if the RAA does not act upon such turning point differences in different rate selections for no background traffic scenario and background traffic scenarios, just like the persistent rate selection tendency of RTS-based loss differentiation mechanism in Section 3, the rate decision most likely lead to performance degradation when dealing with mixed loss effects from background traffic and wireless channel losses. Therefore, as we propose in this subsection, using a model that considers both effects from background traffic and wireless losses in rate selections is a better way to assist RAA in making correct rate decisions.

B. *Rate selection algorithm*

In this section, we describe how BEWARE makes rate selection decisions by using the average expected transmission time derived from previous subsection. BEWARE adopts a rate selection approach similar to [6]. Moreover, BEWARE adopts more careful measures in probing data rates, and implements various schemes in dealing with more dynamic packet transmission statistics from the mixed wireless channel and background traffic environment.

As shown in Fig. 9, the BEWARE design can be broken down into the following tasks:

1) Statistics collection/processing: After the packet transmission completes, transmission environment statistics, including Tbusy, Pbusy, and Pfail, are collected and processed by exponentially weighted moving average (EWMA) to smooth out the biases to the sudden changes in current wireless channel and collision conditions. In addition, BEWARE keeps track other statistics such as number of successful/failed packets of different data rates.

2) Expected packet transmission time calculation: With the environmental parameters collected in the above module, this module use the mathematical model described in previous subsection to calculate the expected packet transmission time. The resultant expected packet transmission time are updated with recent history values by EWMA and fed into rate selection module for processing.

3) Rate probing: Periodically, BEWARE sends packets at a data rate other than the current one to update the expected transmission time of other data rates. In order to avoid the common rate-probing pitfalls reported in [4], BEWARE adopts various measures to ensure probing other data rates is not done very often and the cost is not too high. BEWARE limits the frequency of packet probing to a fraction (~5%) of the total transmission time. BEWARE also limits the number of retries allowed for probing packets to 2 to save costly waiting time for unsuccessful probing. In addition, BEWARE does not probe data rates that suffer from excessive failures for most recent packet attempts, and those whose expected transmission time with no background traffic already exceed the expected transmission time of current operating data rate.

4) Rate selection decisions: The rate selection module constantly compares the expected packet transmission time of current data rate and that of others, and decides to change operating data rate whenever it finds a data rate yields the shorter transmission time (and thus highest throughput). BEWARE also implements a short-term frame loss reaction mechanism in case wireless channel conditions change too rapidly. The rate selection module forces data rate to decrease one level when the packets exhaust all retries for three times consecutively.

V. PERFORMANCE EVALUATION

In this section, we use ns-2 [20] to evaluate the performance of BEWARE and other RTS-based loss differentiation RAAs, including ARF with RTS/CTS (as referred to ARF-RTS) and CARA-1 under various mixed wireless and background traffic scenarios.

A. *Simulation setup*

We enhance the ns-2 simulator to support 802.11a Physical layer (PHY) and Ricean fading model [13]. By default, we set the Ricean distribution parameter, K=6, and Doppler spread f_m = 17Hz (resulted from environment maximum velocity v=1m/s) for performance comparisons. Later in this section, we vary K and f_m to investigate the fading effects on the RAA performance. We simulate scenarios in an infrastructure-based network, which contains one Access Point (AP) and a number of static wireless stations spreading in the network. The traffic sources are UDP flows, and we use saturated traffic as recent IETF measurement studies [21] has shown that highly congested environments represent realistic scenarios.

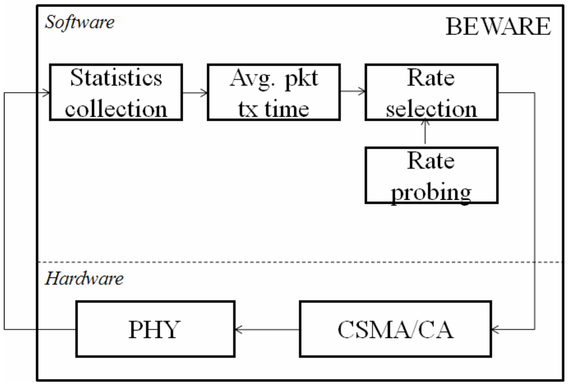


Figure 9. Structure of BEWARE design

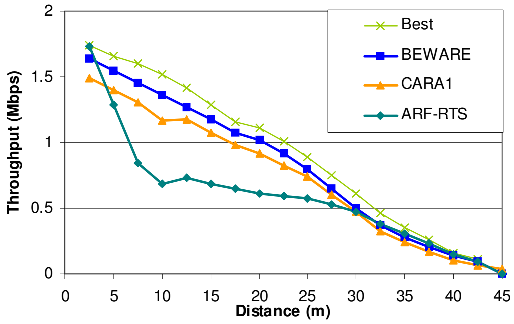


Figure 10. Throughput comparison for Best (best available strategy), BEWARE, CARA1, and ARF with RTS/CTS, with 12 background traffic stations in RTS access mode

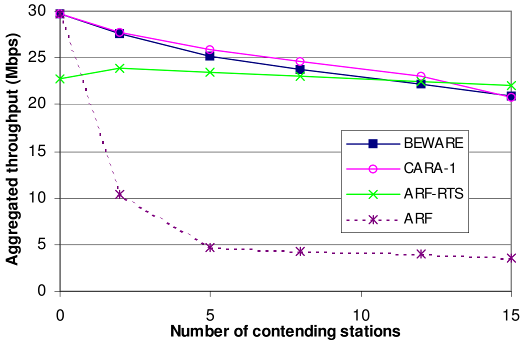


Figure 11. Aggregate throughput comparison for BEWARE, CARA1, ARF with RTS, and ARF in close-by topology with various number of contending stations

B. *Performance of single station with varying distance*

We first focus on RAAs' performance with varying distance under background traffic scenarios. We place 2~12 stations on a circle around the AP within 2 meter radius, and all stations transmit UDP background traffic with RTS access mode. The transmission data rate of background traffic stations is locked at 54Mbps because of very close proximity to AP. We then add one RAA-enable station in the network and measure the RAA's performance by varying the distance between RAA-enable station and AP. We show results with 12 stations transmitting background traffic as an example in Fig. 9, while results with other number of background traffic stations show similar trend. In all cases, the performance of BEWARE follows closely to what is offered by best available strategy by only 10% less in throughput, and the performance of CARA-1 trails behind BEWARE by another 10%-15%. On the other hand, the performance of ARF-RTS significantly derails from the best available strategy when the distance from station to AP is close by to moderate (2.5m~35m). It is because, in this range, the rate selections for no background traffic deviate significantly from the rate selections for this background traffic scenario. As we discussed in Section 3, ARF with RTS loss differentiation suffers from performance degradations by continuing to use the rate selections only suitable for no background traffic.

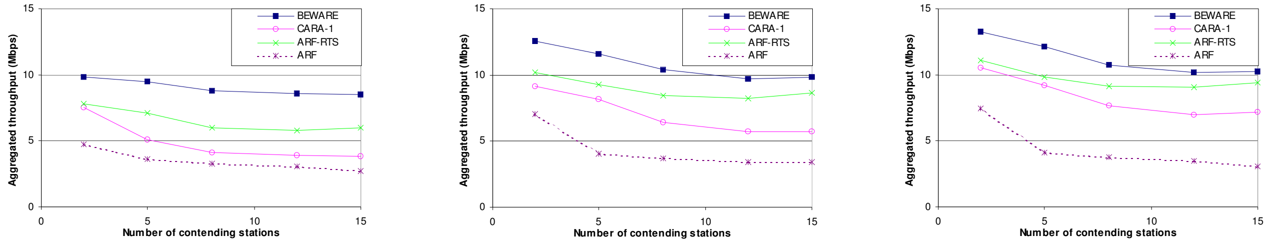
C. *Aggregated performance with varying number of contending stations*

We now evaluate aggregate performance when all stations turn on RAA and operate with the same RAA homogeneously. We first simulate a topology with minimum wireless losses, in which various numbers of stations are uniformly placed at 2.5m away from AP and each station transmits fixed size 1500-byte long UDP traffic. As shown in Fig. 10, ARF's aggregate performance degrades severely due to the "rate poisoning" effect we discussed in Section 3. On the other hand, with the help from RTS loss differentiation, ARF-RTS performs well for any number of contending stations. Furthermore, BEWARE and CARA-1 perform closely and both outperform ARF-RTS in most cases, thanks to the overhead reduction design in CARA-1 and accurate background traffic effect estimation in BEWARE.

Secondly, we simulate a random topology with various numbers of stations randomly scattering in the network with maximum distance 45m away from AP to guarantee no hidden terminals. Each station transmits UDP traffic with random size. As shown in Fig. 11, the performance ranking differs from what we observe in Fig. 10. While ARF still suffers from rate poisoning and performs the worst, CARA-1 no longer outperforms ARF-RTS and ranks second from the worst. It is because, as nodes spreading at different distance to AP, both wireless loss and contention losses affect the default without-RTS data frame transmissions, which cause CARA stations decrease data rate over aggressively. On the other hand, BEWARE still performs the best in random topology. On average, BEWARE outperforms ARF by 200%-250% and ARF-RTS, the best proposed by previous studies, by 20%-25% in aggregate performance.

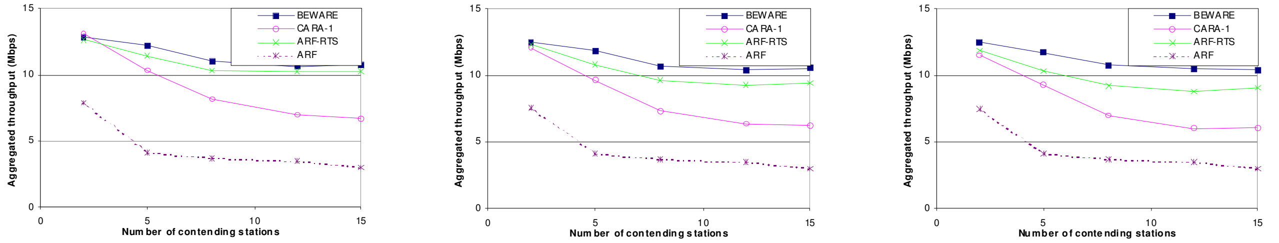
D. *Aggregated performance under various channel fading conditions*

We now compare the performance of different RAAs under various channel fading conditions. We vary the Ricean parameter K and Doppler spread f_m. Note that, as K increases, the line-of-sight component is stronger and the overall channel SNR increases. On the other hand, as f_m increases, the channel condition changes more rapidly. Fig 12 plots the aggregate performance of different RAAs under different K in a random topology similar to what we used in previous sub-section. We can see that, as K increases, the overall throughput all RAAs increases as expected. However, the



(a) *K=0* (b) *K=6* (c) *K=12*

Figure 13. Aggregate throughput comparison for BEWARE, CARA1, ARF with RTS, and ARF in random topology under different Ricean Parameter K



(a) f_m=3.5HZ (v= 0.2 m/s) (b) f_m=10HZ (v= 0.6 m/s) (c) f_m=17HZ (v= 1 m/s)

Figure 14. Aggregate throughput comparison for BEWARE, CARA1, ARF with RTS, and ARF in random topology under different Doppler Spread f_m

ranking of RAA performance remains unchanged. BEWARE outperforms ARF-RTS, CARA-1, and ARF under all different K parameters we studied. We then plot Fig 13 with the aggregate performance of different RAAs under different Doppler spread. We can see that, as f_m decreases, BEWARE still outperforms ARF-RTS in most cases, but the performance gap between BEWARE and ARF-RTS closes. To be more specific, as BEWARE outperforms ARF-RTS by 25% when f_m =17Hz, this advantage decreases to 5% when f_m decreases to 3.5Hz. Previous studies [12][15] reported that, as ARF is designed to increase its rate after several consecutive packet successes, ARF-based RAA tends to yield higher throughput by taking advantage of the slower changing channel environment. However, the performance of ARF degrades when the wireless channel condition changes rapidly. On the other hand, we can see that, as BEWARE yields comparable performance in different f_m environments, BEWARE is robust to both fast-changing and slow-changing wireless channel conditions.

E. Performance with heterogeneous RAA deployments

As rate adaptation is an option that is left open for wireless card vendors to implement, it is not uncommon that there are stations equipped with different RAAs in real world scenarios. Therefore, it is essential to evaluate the performance of different RAAs in heterogeneous scenarios. In this experiment, we evaluate how different RAAs improve the individual and aggregate performance with a gradual upgrade deployment. We consider a network with 12 stations randomly placed within the transmission range of the AP, and transmit UDP traffic with random size. By default, all stations operate with ARF without RTS/CTS, which is considered the baseline scenario. We then gradually upgrade a number of stations with BEWARE or ARF-RTS, and evaluate the aggregate performance improvement over baseline scenario and individual performance improvement of the same station after upgrade. We can see from Fig. 12 that, as the aggregate performance of ARF-RTS improves when upgraded stations added to the network, the individual performance of ARF-RTS actually decreases when less than half of the stations in the network are upgraded. When there are just a few stations upgraded with ARF-RTS, individual performance of upgraded stations decrease due to excessive use of higher data rates as we discuss in Section V-B. Meanwhile, aggregate performance increases as other stations take advantage of the excess loss transmission opportunities incurred by upgraded stations. On the other hand, when there are more and more stations upgraded with ARF-RTS, ARF-RTS stations mutually take advantage of other upgraded stations' loss transmission opportunities, and collectively result in higher aggregate throughput even the rate selections made by these stations are not the most suitable ones for the corresponding scenario. By contrast, both individual and aggregate performance of BEWARE start to improve when just 1 station is upgraded. In addition, as the stations upgraded with BEWARE start to use data rates higher than what is used before upgrade, other stations benefit from the extra free transmission time spared by BEWARE stations, and thus yields higher throughput even they are not upgraded with BEWARE. Note that this is an essential feature that, when incorporating any new algorithm to interoperate with other existing algorithms, the new

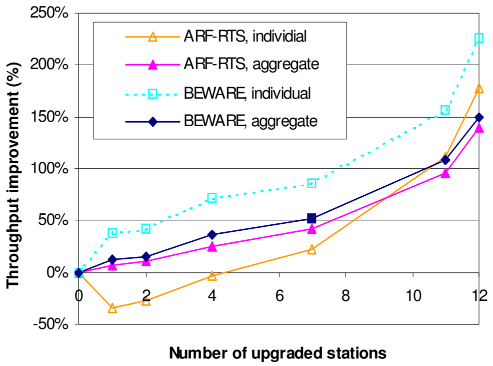


Figure 15. Individual and Aggregate throughput improvement of BEWARE and ARF-RTS with various number of contending stations in heterogeneous deployments

algorithm should not hurt the performance of other existing algorithms.

In summary, with the homogeneous and heterogeneous background traffic scenarios we evaluate in this section, we observe that, while the effectiveness of RTS-based loss differentiation RAAs differ in different scenarios, BEWARE always yields the best performance for most cases. In addition, even with only one station equipped with BEWARE in the network, both individual performance of BEWARE and aggregate network performance improve over the rate-poisoned all-ARF network.

VI. CONCLUSION

In this paper, we first identify that data rate selection strategies of 802.11-based stations should accommodate the different rate selection criterions in different background traffic scenarios. This observation further helps us explain why RTS-based loss differentiation schemes, which are proposed by previous studies to aid rate adaptation algorithms in dealing with collision effects, do not perform well in certain scenarios. In particular, RTS-based loss differentiation hurts the performance by persistently using the same rate selections regardless of background traffic level. Therefore, these observations motivate us to design a rate adaptation algorithm that explicitly addresses wireless and contention factors in its design.

We propose a novel background traffic-aware rate adaptation, BEWARE, that uses an accurate mathematical model to estimate the effectiveness of the data rates in given wireless and contention conditions. We show that the rate selections of BEWARE are close to what are selected by the best available strategy that has global knowledge of network conditions. We also show that, compare to other RTS-based loss differentiation schemes, BEWARE yields the best performance in scenarios we investigated in the paper.

As a work-in-progress, we are working on implementing BEWARE into the real 802.11a wireless card driver. The results of real-world experimentations and related materials will be updated in authors' website [22]. Meanwhile, we also plan to investigate the interactions between rate adaptation algorithms and upper-layer protocols such as TCP. We believe that, as the design of BEWARE fully addresses the wireless and contention factors in MAC layer, it should render the best performance when integrated with upper-layer protocols.

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