A comparative simulation study of rate adaptation algorithms in wireless LANs

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Abstract: Wireless channel condition varies quickly and unpredictably, which is the main reason leading to the low performance of 802.11 wireless local area networks. One effective way to overcome the above problem is rate adaptation, which adaptively selects an appropriate transmission rate according to current channel conditions. A number of rate adaptation algorithms have been proposed in the literatures. However, few of them have been thoroughly evaluated by simulations. It is necessary to conduct a comparative study of these rate adaptation mechanisms, to have a comprehensive view about their impacts on the performance of applications in different channel conditions. In this paper, we perform an extensive comparative simulation study on several well-known rate adaptation algorithms based on ns-3. We quantify their performance for aggregate network throughput in the following two environments: collision-concerned and mobility-concerned. This work is an important step to understand the behaviour of different rate adaptation algorithms.

Keywords: 802.11; wireless local area networks; rate adaptation algorithms; throughput; ns-3; wireless channel conditions.

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1 Introduction

Bit rate adaptation is a critical link-layer mechanism to enhance the performance of 802.11 Wireless Local Area Networks (WLANs), which adopts multiple transmission bit rates in physical layer (Xiao, 2005). While mobility and collisions are two most salient features for current WLANs and post great challenges to rate adaptation (Judd et al., 2008; Musaloiu-E and Terzis, 2008; Chen et al., 2009; Gudipati and Katti, 2011). On the one hand, more and more wireless devices such as 802.11 phones, PDAs, embedded networked sensing devices, or automobiles need the support of varying movement speed. Device mobility results in very dynamic and unpredictable wireless channels, which make rate adaptation difficult to adapt quickly to such channel conditions' variations. On the other hand, with more devices accessing to networks, the possibility of concurrent transmissions caused by multiple contending nodes or hidden terminals is increased due to the contention nature of the 802.11 DCF (Distributed Coordination Function) (Aguayo et al., 2004; Jardosh et al., 2005). This requires that rate adaptation algorithms should be able to detect such collisions, because reducing the bit rate in response to collisions will increase the duration of frame transmission and will exacerbate the collision when employing a traditional medium access method (e.g. exponential back-off scheme) to avoid collision on the next retry (Zhao et al., 2008; Vutukuru et al., 2009). Therefore, it is necessary for rate adaptation algorithms to distinguish collision-induced packet losses from channel-error-induced packet losses. The former is caused by signal collision of multiple concurrent transmissions, while the latter is caused by weak signal due to signal attenuation, channel fading or multi-path fading.

The robustness to collision-induced packet losses and responsiveness to fast channel dynamics due to device mobility are two primary factors that affect the performance of rate adaptation algorithms. In particular, if rate adaptation algorithms are robust to collisions and responsive to channel changes, they can gain more opportunities to transmit frames with higher bit rates or to lower the possibilities of packet losses, and finally improve the performance of networks.

A number of rate adaptation algorithms have been proposed in 802.11 WLANs to achieve one of the above mentioned goals or both of them. However, few of them have been thoroughly and comparatively evaluated on a unified platform. In this paper, we study the performance of four most representative rate adaptation algorithms, namely Onoe (Onoe, see http://madwifi-project.org/browser/madwifi/trunk/ath_rate/onoe), Minstrel (Fietkau, 2006), RRAA (Wong et al., 2006) and CARA (Kim et al., 2010), and compare them with the ideal algorithm, which always selects the optimal rate based on Signal-to-Noise-Ratio (SNR) measurements. The evaluation is conducted in the following two simulation scenarios: collision-concerned and mobility-concerned. The collision-concerned scenarios are used to assess the impact of collision on the performance of rate adaptation algorithms, while the mobility-concerned scenarios are used to evaluate the performance of rate adaptation algorithms in the presence of varying degrees of node mobility.

Our comprehensive performance evaluation of rate adaptation algorithms has the following features.

- These four rate adaptation algorithms have not been compared with each other. The reasons why we choose these algorithms as comparative objects are: (a) Onoe is widely used in the MadWifi driver, and Minstrel is adopted as the default rate adaptation algorithm in the new 802.11 framework in Linux wireless, and will be a replacement of the MadWifi driver; (b) RRAA and CARA are two of the most recently proposed rate adaptation algorithms, which have been implemented in real systems and proved to work well across many scenarios by preliminary evaluations.
- Most of the existing evaluations are conducted either through test-bed experiments or controlled emulations, which use a channel emulator to generate various channel conditions. It is hard to configure many network parameters for both of these two methods. As a result, it is impossible to repeat the results of evaluations. In this paper, we use ns-3 network simulator to conduct simulation evaluations. Ns-3 introduces many new features when compared to ns-2, such as more accurate frame error rate model and channel model, (Miller, 2003; Lacage and Henderson, 2006; Pei and Henderson, 2010). The advantage of simulation over test-bed experiment is that it can evaluate the performance of algorithms in many different scenarios. Our simulations consider different topology settings by considering the following two factors: collisions and mobility. The rest of this paper is organised as follows. In Section 2, we briefly describe the rate adaptation algorithms which are evaluated in the paper. Then, in Section 3, we present simulation model, including the simulation environment and scenarios. Section 4 analyses the simulation results. We discuss related work on rate adaptation algorithms and their performance evaluation in Section 5. Finally, we conclude the paper and present the future research directions.

2 Rate adaptation algorithms under evaluation

In this section, we present rate adaptation algorithms studied in our paper. In this paper, we consider five rate adaptation algorithms: Ideal, Onoe, Minstrel, RRAA and CARA. Table 1 summarises the most important characteristics of these algorithms. Onoe and Minstrel are two collision-ignored rate adaptation schemes. They do not differentiate between collision-induced packet losses and channel-error-induced packet losses. These two algorithms are implemented in MadiWifi driver, which is an open-source driver for wireless chip-sets of Atheros communications. On contrary, RRAA and CARA are collision-aware rate adaptation mechanisms, which use adaptive RTS/CTS exchanges to alleviate the impact of collision-induced packet losses on rate adaptation process. The Ideal algorithm is taken as the benchmark of our evaluations.

Table 1 Characteristics of rate adaptation algorithms under evaluation

	Transmitter -based	*Collision differentiation*	*Link quality metric*	*Rate selection mechanisms*
Ideal	No	Yes	SNR-based	Optimal
Onoe	Yes	No	Frame-based	Sequential
Minstrel	Yes	No	Frame-based	Sequential
RRAA	Yes	Yes	Frame-based	Sequential
CARA	Yes	Yes	Frame-based	Sequential

Detailed descriptions about the five rate adaptation algorithms are given below.

- *Ideal*: t implements an ideal rate control algorithm similar to SNR-based algorithm in spirit, such as RBAR (Holland et al., 2001), CHARM (Judd et al., 2008) and FARA (Rahul et al., 2009). More specifically, every node keeps track of the SNR value of every received packet and sends back this value to the original transmitter by an out-of-band message or other control messages, such as ACKs or CTS frames. Each transmitter keeps track of the last SNR value sent back by the receiver and chooses a proper modulation scheme by looking up a set of SNR thresholds built from modulation-specific SNR/BER curves corresponding to a target Bit Error Rate (BER).
- *Onoe*: This algorithm is well known because it has been used as the default rate adaptation algorithm for previous MadWifi driver. Onoe uses a credit metric to make decision of rate selection. The initial value of credit is set to 0. When it is –1, Onoe decreases the bit rate. When it is up to 10, Onoe increases the current bit rate. The value of the credit is calculated every one second for current bit rate based on packet loss ratio. Figure 1 shows the state transition diagram of calculation of the credit value.
- *Minstrel*: Minstrel is claimed to be one of the best rate control algorithm. Its original version is SampleRate (Bicket, 2005), which is designed and implemented by Bicket, (2005). It uses a four rate-count (r0/c0, r1/c1, r2/c2 and r3/c3) retry chain as in AMRR (Lacage et al., 2004). Minstrel measures the throughput and the probability of success for each rate every 100 ms, and determines the values for the four rates in the retry chain based on these measurement results. Meanwhile, Minstrel uses EWMA (Exponential Weighted Moving Average) to estimate the throughput, which can cope with environmental changes. Minstrel uses 10% of frames to randomly try other rates to collect statistics. Therefore, transmitted frames are classified into normal (90% of frames are this) and look-around sample frames. Table 2 shows the rate used in each retry based on the measurements of these two kinds of frames. For example, for the look-around sample frames, when the randomly selected rate is lower than the rate which has the best throughput, the rate which has the best throughput is chosen as r0, and r1 is set to the randomly selected rate, r2 is set to the rate which achieves the best probability of success and r3 is set to the lowest base rate.
- *RRAA*: RAA uses loss ratio within a short time window (6–40 frames) to access the channel and opportunistically adapts the runtime transmission rate to dynamic channel variations. The loss ratio is the ratio of the number of lost frames over estimation window to the total. Each rate is associated with three parameters: an estimation window size, a maximum tolerable loss threshold (MTL) and an opportunistic rate increase threshold (ORI). These thresholds are defined as:

$$\begin{aligned} P &= \frac{\#\_lost\_frames}{\#\_transmitted\_frames}, \\ P^*(R) &= 1 - \frac{Throughput(R_{)}}{Throughput(R)} = 1 - \frac{tx\_time(R)}{tx\_time(R_{)}}, \\ P_{MTL} &= \alpha \cdot P^*(R), \\ P_{ORI} &= \frac{P_{MTL}(R^+)}{\beta}. \end{aligned} \tag{1}$$

  It decreases the current rate to the next lower one if the loss ratio is larger than P_{MTL}, and it increases to the next higher rate if the loss ratio is smaller than P_{ORT}.

  To be robust against hidden terminals, RRAA uses an adaptive RTS/CTS filter to suppress collision losses. The basic ideal is to leverage the per-frame RTS/CTS option, and selectively turns on RTS/CTS exchange to suppress collision losses. An *RTSWnd* parameter is used to determine when to turn on or off the RTS/CTS function. Table 3 shows how the value of *RTSWnd* is changed. *RTSWnd* is initially set to 0, which disables the RTS/CTS function.
- *CARA*: CARA builds upon ARF (Kamerman and Monteban, 1997) and uses an adaptive RTS/CTS mechanism to prevent collision-induced losses. It uses the count of consecutive failed and successful frame transmissions as indicators to select the transmission rate. When a packet is lost, it enables the RTS/CTS mechanism. If two consecutive packets are lost, it decreases to the next lower rate. When ten consecutive packets are transmitted successfully, it increases to the next higher rate.

Figure 1 State transition diagram of computing the credit value used in Onoe

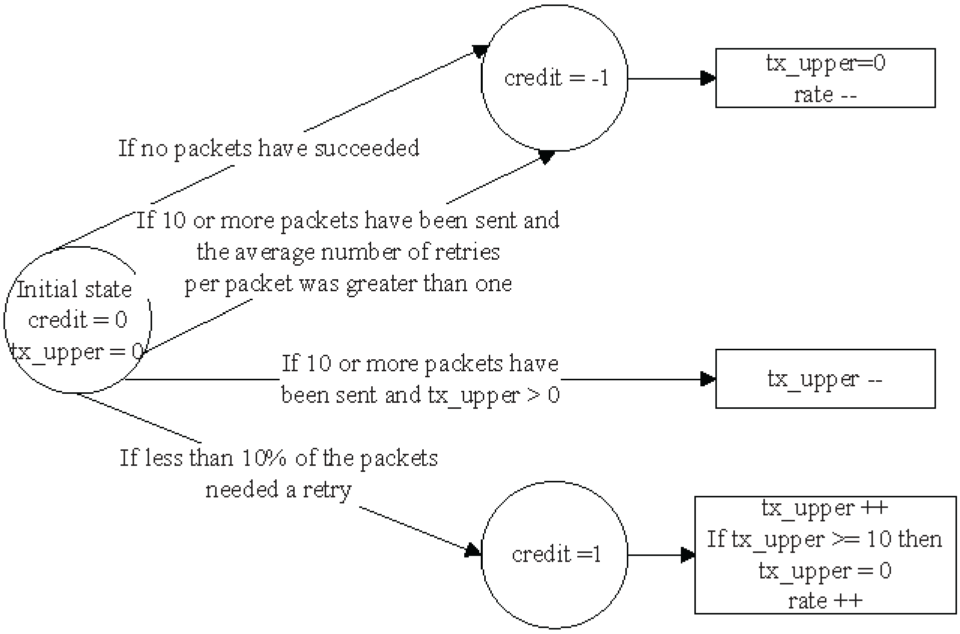


Table 2 Rate retry-chain used in Minstrel

Multi-rate retry chain	*Look-around rate*		*Normal rate*
	Random < *best*	*Random* > *best*	
r0/c0	Best throughput	Random rate	Best throughput
r1/c1	Random rate	Best throughput	Next best throughput
r2/c2	Best Probability	Best probability	Best probability
r3/c3	Lowest base rate	Lowest base rate	Lowest base rate

Table 3 *RTSWnd* parameter maintained by RRAA

	RTS/CTS enabled	*RTS/CTS disabled*
Packet succeeded	*RTSWnd*	*RTSWnd*/2
Packet lost	*RTSWnd*/2	*RTSWnd* + 1

3 The simulation model

In this section, we present the simulation environment and scenarios, under which the evaluation is carried out.

3.1 Simulation environment

Our simulation study is based on ns-3, since it provides a realistic frame error rate model for different modulation and coding schemes and an accurate wireless channel model for diverse environments. In our simulations, we considered different topology settings focusing on the following two factors: collision and mobility. Tables 4 and 5 summarise the values of network parameters configured in simulations. The SNR thresholds are built through looking into the respective modulation-specific SNR/BER curves with a target BER 10e-6 based on the NistErrorRateModel (Pei and Henderson, 2010).

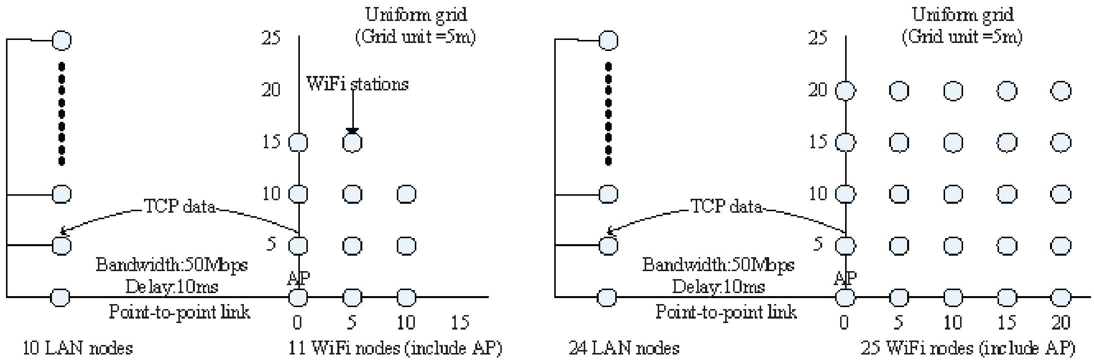
Table 4 Simulation environment parameters and their values used in simulations

Parameters	*Value*
Physical standard	802.11a
ErrorRateModel	NistErrorRateModel
Channel delay model	ConstantSpeedPropagationDelayModel
Channel loss model	LogDistancePropagationLossModel
MAC(Station/AP) type	StaWifiMac/ApWifiMac
Application data rate	1 Mbps
Packet size	1024 bytes
Number of packets	1200 packets
Number of nodes	10/24 nodes
Mobility model	RandomDirectional2dMobilityModel
Mobility speed	RandomVariable: UniformVariable (15.0 mps, 20.0 mps)
Simulation topology (Wifi nodes)	Grid, rectangle range: (–100 m, 100 m, –100 m, 100 m)
Experiment times for every value	5

Table 5 Bit rates supported in 802.11a and SNR-rate look-up table based on our configurations

Bit rate	*Modulation*	*Coding rate*	*SNR threshold (BER = 10e-6)*
6 Mbps	BPSK	1/2	2.46851
9 Mbps	BPSK	3/4	4.80368
12 Mbps	QPSK	1/2	4.93702
18 Mbps	QPSK	3/4	9.60737
24 Mbps	QAM-16	1/2	22.2137
36 Mbps	QAM-16	3/4	45.4008
48 Mbps	QAM-64	2/3	135.384
54 Mbps	QAM-64	3/4	181.051

Figure 2 Simulation topology used in our study: (left) 10-node static/mobile scenario and (right) 24-node static/mobile scenario



We use the throughput of TCP traffics as the metric to evaluate the performance of different rate adaptation algorithms, because applications like TCP and VoIP are lowly tolerant to packet losses, and therefore require more responsive and accurate rate adaptation algorithms to work well. While previous work mostly uses UDP throughput as a metric of performance, we believe that gains obtained on UDP traffics without congestion control are hard to realise in most applications.

3.2 Simulation scenarios

In order to analyse the robustness to collision losses and responsiveness to channel variations for different rate adaptation algorithms, we consider the following two infrastructure scenarios: collision-concerned and mobility-concerned. In both scenarios, 10/24 Wifi stations are deployed into a grid topology, either be static or mobile. In mobile environments, the movement of Wifi stations is based on the two-dimensional random direction mobility model. A Wifi AP is located at the lower left corner, and the AP is connected to a 10/24 nodes Local Area Network (LAN) via a point-to-point link, as shown in Figure 2. We establish 10/24 TCP connections from Wifi stations to LAN nodes, with a continuous constant data rate of 1 Mbps. In all scenarios, the Wifi AP remains static. The specific configured simulation parameters are listed in Tables 4 and 5. From these two scenarios, we analyse the robustness and the responsiveness of different rate adaptation algorithms.

Collision-concerned simulation scenario: This simulation scenario aims to analyse and reveal how collisions affect the performance of rate adaptation algorithms. To achieve this goal, we conduct simulation evaluations using different number of Wifi nodes both in static and mobile scenarios. The more Wifi nodes are deployed in the networks, the higher possibility of packets collisions will be induced. We study the performance of collision-ignored and collision-aware rate adaptation mechanisms with different numbers of Wifi nodes, and analyse the robustness of different algorithms to collision-induced packet losses. Meanwhile, we study the stability of rate adaptation algorithms under these simulation scenarios.

Mobility-concerned simulation scenario: The main objective of this scenario is to evaluate the impact of the Wifi nodes' mobility on the performance of rate adaptation algorithms, namely their responsiveness to channel condition variations. In order to reveal how node's mobility affects the performance of networks in terms of throughput, we compare the performance of different rate adaptation algorithms between the scenarios with static Wifi stations and mobile Wifi stations with different node density.

4 Performance analysis

This section presents the results of performance evaluation of the predicted rate adaptation algorithms, through two simulation scenarios described in the previous section.

4.1 Impact of collision

In this section, we mainly evaluate the impact of collision-induced packet losses on the performance of Onoe, Minstrel, RRAA and CARA.

Results: Table 6 gives the ratio of aggregate throughput of Onoe, Minstrel, RRAA and CARA to Ideal's. In general, with the number of nodes increases, the aggregate throughput of all four algorithms decreases dramatically, no matter in static or mobile environment. This is most noticeable for RRAA algorithm, which goes down from 83.17% to 51.44% in static scenario and 81.34% to 22.91% in mobile environment. CARA works better than RRAA and Minstrel in almost all scenarios, especially in 10-node static environment, it reaches the upper bound produced by Ideal. While Onoe shows the worst performance among all testing schemes in all scenarios, but none of them works best across all environments.

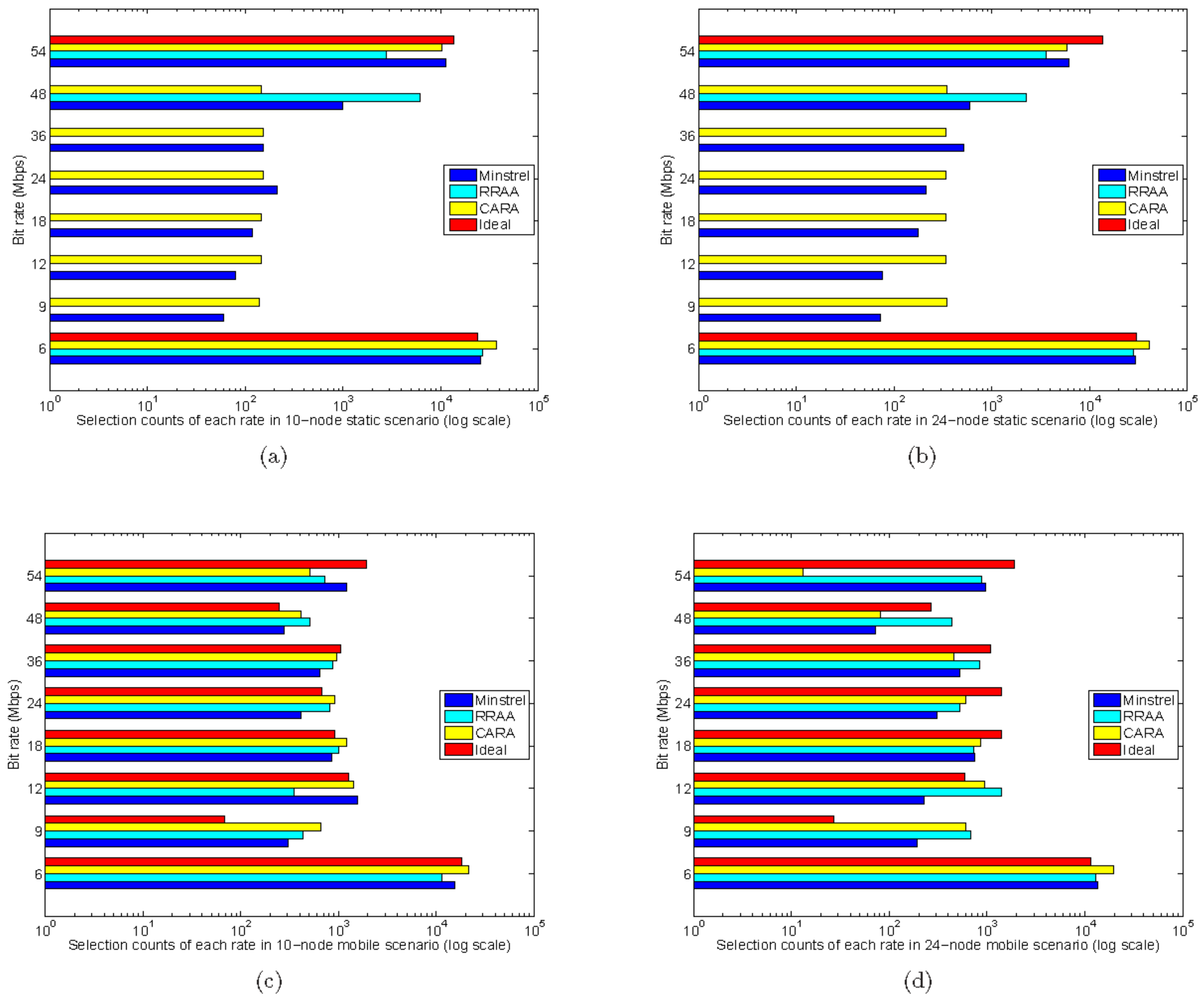
Table 6 Aggregate throughput ratio of Onoe, Minstrel, RRAA and CARA to Ideals

Static or mobile	*Number of nodes*	*Onoe*	*Minstrel*	*RRAA*	*CARA*
2*Static environment	10	37.5%	100%	83.17%	99.57%
	24	24.5%	72.83%	51.44%	74.6%
2*Mobile environment	10	50.07%	74.36%	81.34%	80.76%
	24	24.8%	37.73%	22.91%	42.04%

In 10-node static scenario, Minstrel performs the highest throughput compared to other three algorithms, but its performance decreases when the number of nodes increases. CARA outperforms all the other methods in almost all the scenarios. This is because CARA uses an aggressive adaptive collision differentiation mechanism, and the overhead incurred by RTS/CTS frames is compensated by a more accurate rate selection result. Another interesting observation is that RRAA yields lower throughput than Minstrel and CARA in almost all scenarios, especially in 24-node static/mobile scenarios, it performs very poorly, and achieves only 51.44% and 22.91% of Ideal's throughput, respectively. The main reason for this result is that in the denser networks, the contention becomes more serious, and more collision-induced packet losses take place. RRAA reacts to short-term frame loss ratio and reduces its bit rate regardless of collision-induced or channel-error-induced frame losses. This results in RTS/CTS exchanges being constantly turned on without any real benefit.

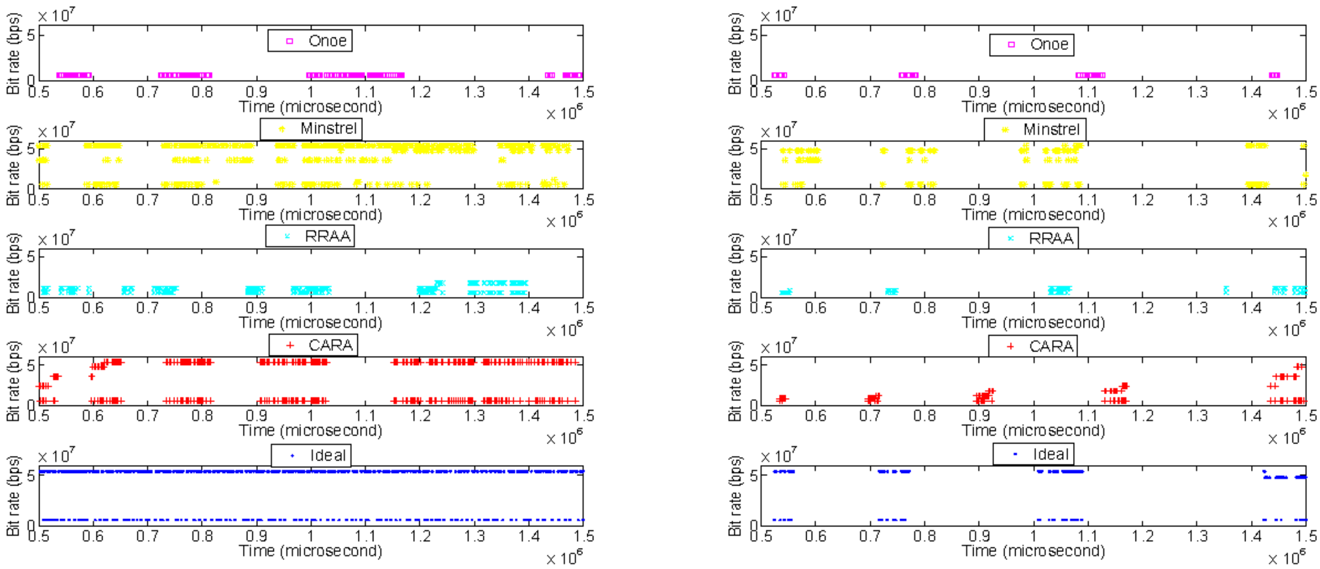
The above observation can also be validated by Figure 3, which shows the rate selection counts for Minstrel, RRAA, CARA and Ideal in all scenarios. We observe that Onoe selects the rate of 6 Mbps in the whole simulation. This is due to its conservative rate selection schemes and demonstrates why it works worst among all evaluated algorithms. RRAA only uses 6, 48 and 54 Mbps three rates in static scenarios, which is close to Ideal's selection results. But RRAA's aggregate throughput is lower than that of CARA and Minstrel, which indicates that RRAA transmits packets at high-data rate at the expense of frequently RTS/CTS exchanges. Therefore, RRAA obtains lower throughput than that of Minstrel and CARA.

Figure 3 Selection counts of each rate by Minstrel, RRAA, CARA and Ideal. Onoe always selects the rate of 6 Mbps: (a) 10-node static scenario, (b) 24-node static scenario, (c) 10-node mobile scenario and (d) 24-node mobile scenario (see online version for colours)



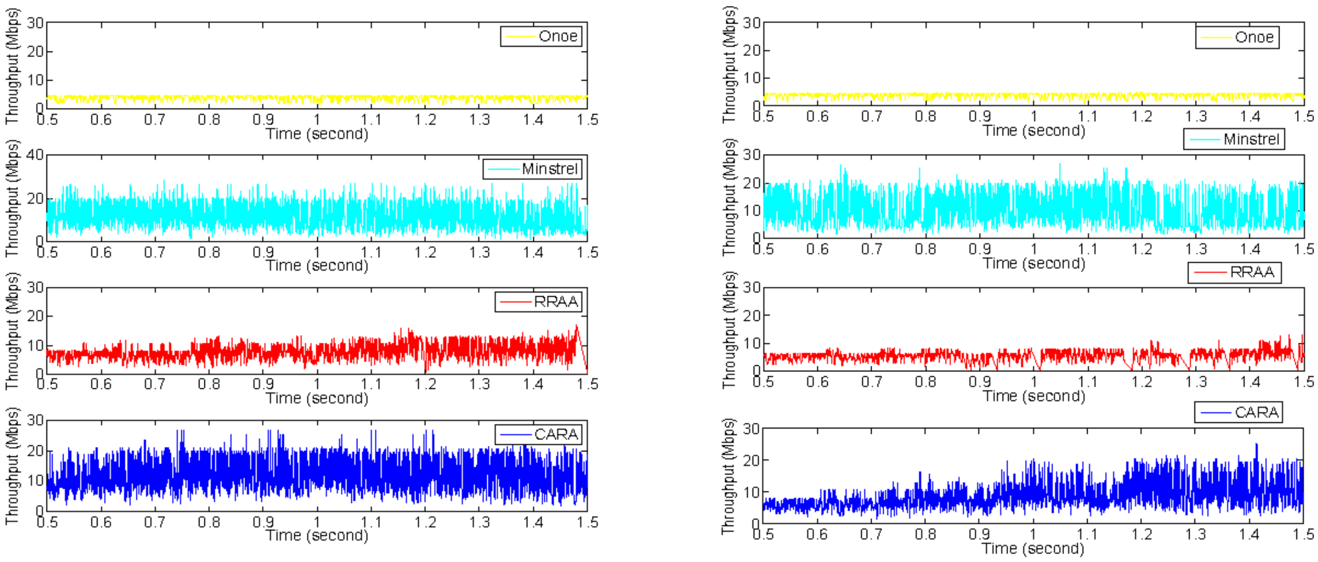
In order to have a good understanding on how and why CARA outperforms other algorithms in almost all scenarios, we investigate the mobile scenario in more depth and study the cause of the observed difference in throughput by plotting the instant transmission rate and throughput for the 10-node and 24-node mobile scenarios in Figures 4 and 5. As shown in Figures 4 and 5, CARA almost always selects optimal rate closed to Ideal and yields higher and more stable instant throughput than others' with a few exceptions. The selection of bit rate by Minstrel and CARA is more accurate than RRAA in both two scenarios. Minstrel shows more opportunities to transmit frames in 10-node mobile scenario due to its indifference of collisions. However, in high dynamic and interfering scenario, Minstrel suffers instant throughput fluctuation because of its frequent rate overselection or underselection. RRAA selects relative accurate rate at the expense of frequent RTS/CTS exchanges, but its instant throughput is low and fluctuates frequently. This is partially because of fewer opportunities to transmit frames suppressed by RTS/CTS frames. From this point, we learn that RRAA's adaptive RTS/CTS mechanism is inefficient in preventing collisions and incurs high overhead.

Figure 4 Comparison of instant rate selection results over time for all testing algorithms: (a) 10-node mobile scenario and (b) 24-node mobile scenario (see online version for colours)



(a) (b)

Figure 5 Instant throughput achieved by different algorithms over time: (a) 10-node mobile scenario (b) 24-node mobile scenario (see online version for colours)



(a) (b)

Implications: Collision-induced packet losses adversely impact on the performance of rate adaptation algorithms. A rate adaptation algorithm that reduces the transmit rate in response to collision-induced packet losses increases the contention on the channel and exacerbates the interference. If the rate adaptation algorithm cannot identify collisions, it may lose many opportunities to send packets with a more reliable or higher transmission rate. Like Onoe, due to its conservative rate selection mechanism, it can only achieve about 30% throughput of Ideal's performance in almost all scenarios. However, a responsive rate adaptation algorithm that reacts to short-term frame loss rate faces the danger of reacting to interference too aggressively. Like RRAA and CARA, their RTS/CTS exchanging overhead may incur a performance penalty when the collision becomes serious. Therefore, there is a trade-off between benefits from collision identification and penalty incurred by collision-induced packet losses.

4.2 Impact of mobility

In this section, we focus on the impact of node mobility on the performance of evaluated rate adaptation algorithms. While collision-aware setting mainly assesses the stability and the robustness of a rate adaptation algorithm, the mobility-aware setting gauges their responsiveness to varying channel conditions.

Results: Figures 6 and 7 show the simulation results on aggregate throughput in 10-node and 24-node static/mobile scenarios, respectively. As shown in Figures 6 and 7, all algorithms suffer severe throughput reduction in the presence of different degrees of node mobility. The throughput degradation of Onoe, Minstrel, RRAA and CARA in 10-node mobile scenario compared to the corresponding static scenario are: 7.28%, 48.38%, 32.07% and 43.67%. The reduction is more obvious in 24-node scenarios, which are 12.87%, 55.4%, 61.67% and 51.48%. Ideal also suffers throughput decrease, but it works a little better in more contending nodes environment. From these results, we can see that no algorithms can work efficiently in mobile environment, especially in scenarios with high-level interference. The SNR-based algorithm Ideal can track the channel state more timely because it selects the transmission rate based on single-received packet's SNR, so it significantly outperforms all other algorithms for the vast majority of the traces.

To get a deep understanding of mechanisms that every rate adaptation algorithm works in mobile environment, we dump the trace of chosen bit rate and SNR value variations over time in 10-node and 24 node static/mobile scenarios. Owing to the space limitations, we only plot the result charts of Onoe, CARA and Ideal algorithms between simulation time 0.5 s and 1.5 s in Figures 8 and 9. The corresponding simulation results of RRAA and Minstrel are not shown in Figures 8 and 9, but we still give their results analysis in the following section.

Figure 6 Aggregate throughput achieved by Onoe, Minstrel, RRAA, CARA and Ideal in 10-node static/mobile scenarios (see online version for colours)

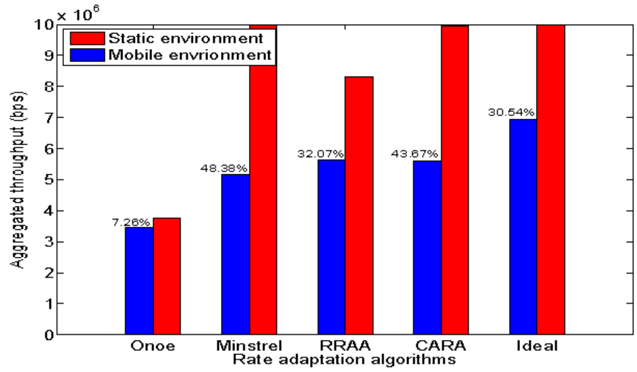
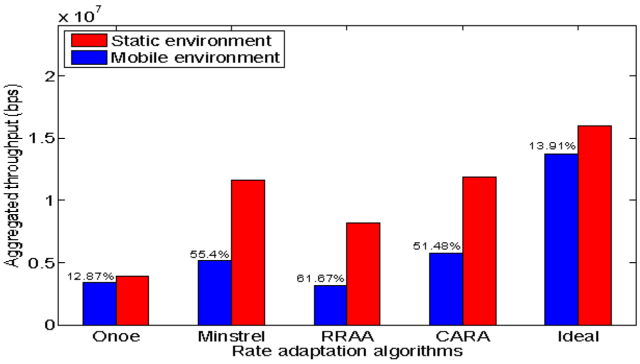


Figure 7 Aggregate throughput achieved by Onoe, Minstrel, RRAA, CARA and Ideal in 24-node static/mobile scenarios (see online version for colours)

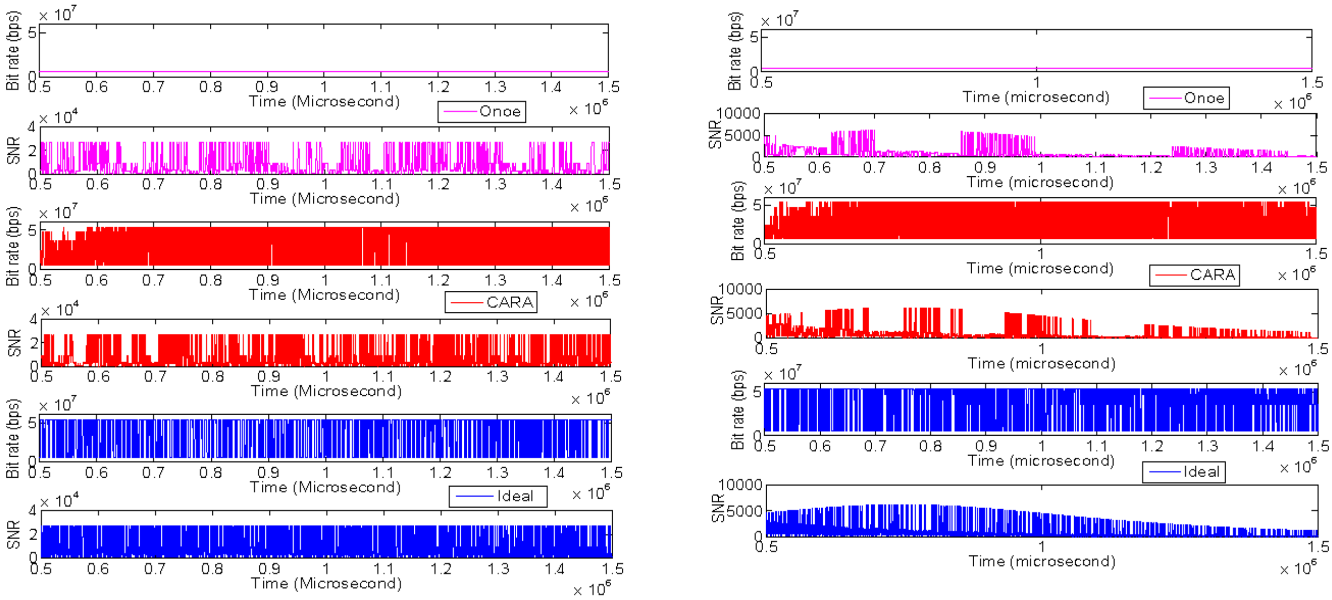


Based on these simulation results, we find that the channel state varies in a wider range and more frequently in mobile scenarios. Onoe cannot track the fast changes as shown in figures. Its transmission rate remains the same in the whole simulation time because of its slow adaptation mechanism. However, Ideal selects a higher rate between 1.1 and 1.5 s, because of the inaccurate SNR estimation based on theoretical calculation. This result also demonstrates that single SNR value cannot reflect the real channel conditions, especially in high-level interference and node mobility environment.

Another interesting observation is that although the selected bit rate cannot match well with the SNR value, CARA still can achieve a certain level of throughput. For example, in 24-node mobile scenario, CARA achieves the highest throughput than other three algorithms. This is because the aggressively adaptive RTS/CTS mechanism of CARA suppresses the collisions and opportunistically chooses a high-bit rate to transmit packets, which compensates the overhead incurred by the RTS/CTS exchanges. On the other hand, RRAA performs very poorly in 24-node mobile scenario, even below Onoe (22.91% and 24.8%). This is because of RRAAs slow response to channel changes. At high-bit rate, it requires more time to achieve a rate update decision. This is also demonstrated in Figure 5, RRAA has lower instant throughput than that of Minstrel and CARA.

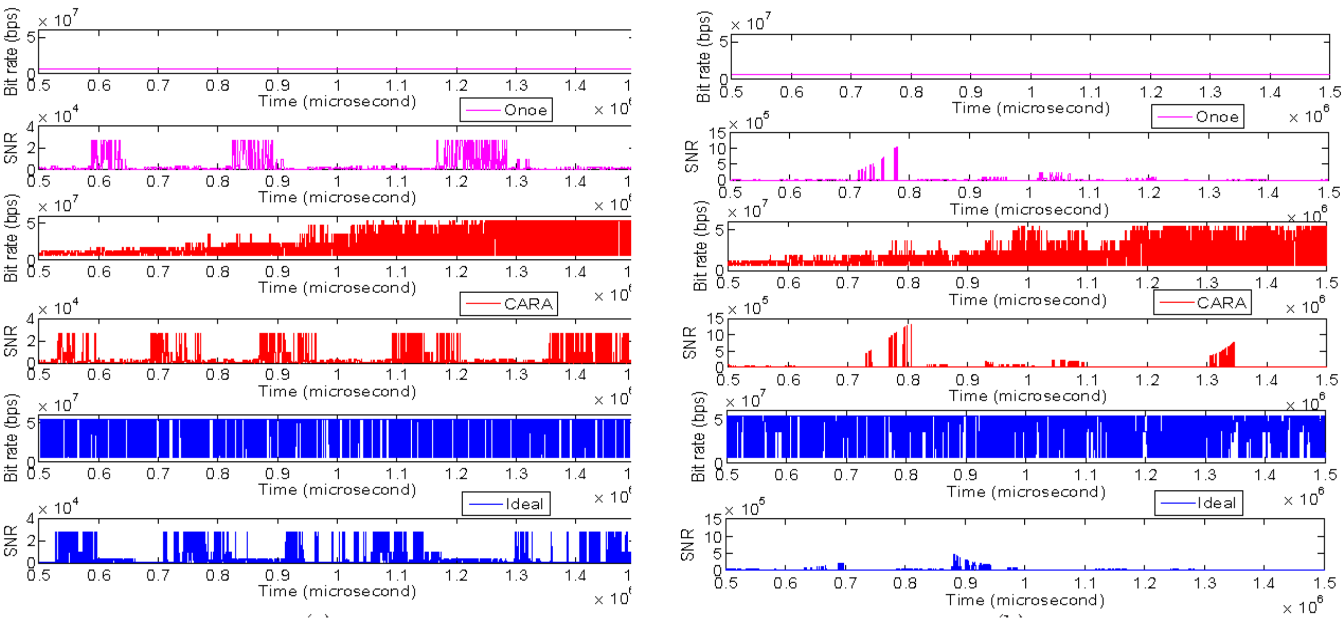
Implications: The quick and accurate response to link condition changes is very important to make rate adaptation decision. Both frame-based and SNR-based schemes have low throughput in dynamic scenarios, and the low performance is mainly due to the inaccuracies of rate choice and slow adaptation to link status dynamics. For the frame-based algorithms, the sequential rate stepping is inefficient in the mobile environment and results in underselection of the bit rate. On the contrary, SNR-based protocols can make overselection of the ideal rate due to the inaccurate SNR estimation, which is based on the theoretical relationship between SNR and channel BER across various modulations. Besides that external interference makes the rate selection more challenging. Collision-ignored rate selection causes an increasing number of losses, and triggers the frame-based algorithms to underselect the transmission rate.

Figure 8 Instant SNR and bit rate over time for Onoe, CARA and Ideal, (a) 10-node static scenario (b) 10-node mobile scenario (see online version for colours)



(a) (b)

Figure 9 Instant SNR and bit rate over time for Onoe, CARA and Ideal, (a) 24-node static scenario (b) 24-node mobile scenario (see online version for colours)



(a) (b)

4.3 Summary

We have thoroughly analysed and compared several well-known rate adaptation algorithms, namely Onoe, Minstrel, RRAA and CARA, to Ideal mechanism. We first show the collision-induced packet losses have bad effects on rate adaptation mechanisms. Then, we evaluate their performance variation with different degrees of mobility. In particular, following general lessons are learnt from this simulation study.

Collision-aware rate adaptation algorithms are more robust and stable than collision-ignored algorithms in high-level interfering scenarios. However, there is a trade-off between benefit from collision identification and performance degradation incurred by collision-induced packet losses. Algorithms that use RTS/CTS exchanges to cope with collision problem may incur high overhead and should be elaborately designed to adapt to different channel conditions. Frame-based rate adaptation algorithms are less responsive to channel dynamics than SNR-based algorithms, because they require multiple frame transmissions to accurately estimate channel state at any bit rate. On the other hand, SNR-based schemes react more relative quickly to channel variations, but it is difficult to accurately measure SNR value in current commercial 802.11 devices due to hardware calibration issues and the SNR–BER relationship changes with different propagation environments, especially in high-dynamic environments. Also, the value of SNR measured at the start of the packet does not capture the variations in SNR that might occur during the packet transmission due to fading. Therefore, SNR-based algorithms need in-situ SNR training to cope with the inaccuracy incurred by single SNR value. In addition, SNR-based algorithms are complicated in hardware and software, and are difficult to be implemented on current devices. Almost all evaluated algorithms show dramatic throughput degradation with increased number of nodes and degree of node mobility. But there is one exception: Onoe achieves a little better performance in dense mobile scenarios, but as the number of nodes increases, its improvement in throughput becomes unnoticeable. In general, Onoe performs the worst out of all algorithms in almost all environments. This can be explained by its way of operation, which is conservative in rate selection and sensitive to the individual packet failure. Minstrel works best in static environment among frame-based schemes. In particular, it outperforms the collision-aware methods, namely RRAA and CARA. This is mainly because of the RTS/CTS control overhead of RRAA and CARA incurred in the static environment, where collision is not a dominant factor that induces packet losses. However, with the increased collision and mobility, its performance decreases quickly due to lack of collision identification ability. CARA is more likely to make correct rate selection decisions than other frame-based methods in various environments. In particular, it is more responsive to significant channel variations incurred by node mobility and more robust to collision-induced packet losses. So in the view of simplicity of implementation, CARA protocol is a good choice for system designer. RRAA achieves the worst performance in dynamic and congested scenario. The main reason lies in its heavy overhead of frequent collision detection and slow responsiveness to channel dynamics which results in many rate underselections. It should be noted that none of the currently proposed algorithms can provide good performance in mobile environments with frequent collisions. This is because all of them cannot adapt quickly and accurately to dynamic link status. The adaptive RTS/CTS mechanisms cannot eliminate the impact of collision on rate selection. Therefore, some improvement can be done, and a much higher throughput could be achieved.

5 Related work

This section discusses previous research work related to rate adaptation algorithms and their performance evaluation.

5.1 Rate adaptation algorithms

There are a large body of research work on rate adaptation algorithms in the literature. Existing rate adaptation schemes can be broadly classified into four categories: frame-based, SNR-based, PHY-based and others.

Frame-based rate adaptation algorithms: Many frame-based rate adaptation algorithms have been proposed. Frame-based protocols are the most commonly implemented due to their transmitter-based simplicity. These schemes use sequential rate stepping based upon either consecutive success and failures or delivery ratio over a time window based upon historical performance of modulation rates. The most recent ones are Onoe, Minstrel, RRAA and CARA. Other frame-based algorithms include ARF (Kamerman and Monteban, 1997), AARF (Lacage et al., 2004) and SampleRate (Bicket, 2005). ARF attempts to use higher transmission rate after consecutive transmission successes and reverts to lower rates after failures. AARF is an adaptive variant of the ARF for low latency and high latency systems that improves upon ARF to provide both short-term and long-term adaptation. SampleRate tries to maximise the throughput by estimating per-frame transmission time at each rate and selects the transmission rate with the lowest expected per-frame transmission time. RRAA and CARA are two algorithms that use adaptive RTS/CTS control frames to cope with collision-induced packets losses.

SNR-based rate adaptation algorithms: In contrast to frame-based schemes, SNR-based algorithms use Received Signal Strength (RSS) provided by wireless devices to select the transmission rate. Since the theoretical relationship between SNR and BER is well-known across various bit rates, it is conceivable that SNR estimation of received frames can accurately reflect the real status of channels (Ferrari et al., 2008), and can select the best transmission rate based on SNR–BER look-up table to maximise throughput. The most recent SNR-based ones include FARA (Rahul et al., 2009) and ESNR (Halperin et al., 2010). FARA exploits frequency diversity and leverages OFDM, computing per-frequency SNRs using normal frame transmission at the receiver, and enables the sender to adapt the bit rate independently across frequencies based on these per-frequency SNRs. ESNR uses effective SNR to capture frequency-selective fading, and predicts frame delivery based on Channel State Information (CSI) reported by 802.11n NICs, a much richer source of information than RSS. Then ESNR computes the highest rate configuration that is predicted to successfully deliver packets (packet reception ratio >90%). Other SNR-based methods include RBAR, OAR (Sadeghi et al., 2002), CHARM (Judd et al., 2008) and RAM (Chen et al., 2009). RBAR uses RTS/CTS exchange at the beginning of a packet to estimate SNR at the receiver side, and picks the bit rate accordingly. OAR is built on RBAR. Its key ideal is to opportunistically send multiple back-to-back packets when the channel condition is good. Unlike RBAR and OAR, CHARM leverages channel reciprocity to obtain channel information at the sender side, so the information is available to the transmitter without incurring RTS/CTS overhead. RAM uses a receiver-based approach to handle channel asymmetry and a conservative SNR prediction algorithm to deal with high-channel fluctuation in mobile environment. RAM allows the receiver to convey the feedback information in a creative manner via ACK transmission rate variation, which does not require changes of device firmware and hence is implementable at the device driver level.

PHY-based rate adaptation algorithms: In contrast to above two kinds of methods, PHY-based approaches use neither frame receptions nor SNR estimates but directly exploit physical layer information to select bit rate. There are two typical schemes: SoftRate (Vutukuru et al., 2009) and AccuRate (Sen et al., 2010). SoftRate uses physical layer confidence value to estimate a packet's BER, computed from the dispersion of the received symbols from their nearest constellation symbols. By comparing the BER against an empirically generated look-up table, the transmitter picks a good bit rate for subsequent transmissions. SoftRate is the first to exploit physical layer information for rate adaptation. The main ideal of AccuRate is to capture the channel behaviour through symbol level dispersions, and replay these dispersions on different rate encodings of the same packet, thereby jump to the optimal rate in one step. ARA (Aditya and Sachin, 2010) and Strider (Gudipati and Katti, 2011) also belong to this category. Strider is a novel code that is rateless and collision-resilient. Rateless code allows a sender to effectively achieve almost the optimal rate without knowing the channel state varies. Collision-resilient code allows a receiver to decode packets from collisions.

PHY-based rate adaptation algorithms work much better than frame-based and SNR-based. However, they need to modify the physical layer modules and cannot be implemented on current deployed commodity devices. AccuRate incurs high per-packet processing overhead and is impractical to implement in high-speed systems.

Others: MiRA (Pefkianakis et al., 2010) and RapidSample (Ravindranath et al., 2011) are most recent research results of rate adaptation. MiRA is a new rate adaptation algorithm for 802.11n MIMO systems and is essentially frame-based. RapidSample uses sensor hints, such as device's state of motion, speed, direction of movement, or position, to guide the rate selection. There are also many other methods (Haratcherev et al., 2004; Zhang et al., 2008; Rayanchu et al., 2008; Shankar et al., 2008; Pejovic and Belding, 2011).

5.2 *Performance evaluation for rate adaptation algorithms*

There are little works comparing the performance of rate adaptation algorithms based on simulations. Most of previous works are either conducted in a real environment or in a controlled emulator-based environment. Furthermore, many of these studies focus on static networks, or use very simple topology, such as only a few mobile nodes for mobile scenario evaluation.

ARF, AARF, Onoe and SampleRate are evaluated in the work of Bicket (2005). The main findings are that: (a) SampleRate outperforms ARF, AARF. (b) Onoe and SampleRate perform very close to the performance of the best fixed rate. However, the impact of mobility is not evaluated. In our simulation study, we find that Onoe performs better in mobile environment. Wong et al. (2006) evaluate RRAA, SampleRate, ARF and AARF in a realistic 802.11a/b networks with various settings, such as static, mobile and hidden-station settings. The main result is that RRAA consistently outperforms all other three algorithms. In our simulation study, we find that RRAA suffers severe performance degradation in the presence of collisions and mobility.

CHARM, AMRR, Onoe and SampleRate are evaluated both in real and controlled emulator-based environment (Judd et al., 2008). Judd et al. consider both static and mobile scenarios with UDP traffic. The evaluation states that Onoe performs poorly in all scenarios. We find it is true in our simulation scenarios. Also it demonstrates that CHARM outperforms all other three algorithms for the vast majority of the traces. However, they only use two nodes in mobile environment.

Joseph and Edward (2008) evaluate ARF, RRAA, RBAR and OAR algorithms on the WARP platform both in controlled emulator-based and real environment. The evaluation results show that: (a) frame-based algorithms underselect in the presence of fast-fading and interference and are unable to track channel changes in mobile environment. (b) SNR-based protocols are susceptible to overselection from the ideal rate and need in-situ training. We find this is true in our simulation study. However, we also find that RRAA works poorly in the presence of high-level interference and mobility. They consider very simple scenarios and do not evaluate the impact of hidden terminals.

Our simulation study is much closer to the work conducted by SoftRate, which conducted trace-driven simulations in ns-3 for SoftRate, RRAA, RBAR, and CHARM. The evaluation results show that: (a) SoftRate achieves throughput gains of up to two times over SampleRate and RRAA, and four times over RBAR and CHARM. (b) RRAA's adaptive RTS/CTS schemes work inefficiently in the presence of interference. We have confirmed these results in our simulations.

6 Conclusion and future work

In this paper, we have conducted an extensive comparative simulation study of several well-known rate adaptation algorithms using ns-3 simulator. Ns-3 simulator provides accurate wireless channel models and calculation methods of packet error rate, which improves the confidence of our simulation results. In our simulations, we did not consider the impact of traffic pattern on the performance of rate adaptation algorithms, which leaves as our future work.

The results presented in the paper demonstrate that research on rate adaptation is challenging and far from being completed, especially in recent extremely complicated communication environments. For example, more and more mobile equipments need to access the networks, which will lead to more congested wireless bands and more collisions. Furthermore, different applications have different node motion patterns, which will make the link highly dynamic and unpredictable. Based on our achieved results, all the rate adaptation methods under evaluation are unqualified for the future application scenarios, in the sense that they cannot promptly and accurately differentiate collision-induced packet losses from channel-error-induced packet losses. Besides that they are unable to respond quickly to changes of channel condition in highly dynamic environments.

We think there is room for improvement, especially with the help of hint information gained from the sensors equipped by nodes themselves (Ravindranath et al., 2011). In our future work, we will focus on how to utilise the sensor hints to improve the accuracy of collision identification and rate selection, and then validate our ideas on a test-bed.

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