EasiRA: A Hybrid Rate Adaptation Scheme for 802.11 Mobile Wireless Access Networks

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***Abstract*—Rate adaptation, which adapts transmission bit rate according to current wireless link conditions, is a fundamental mechanism used by link-layer protocols to improve the performance of 802.11 wireless access networks in terms of throughput. However, rate adaptation faces to severe challenges due to more and more congested and dynamic wireless links. In this paper, we design a hybrid rate adaptation scheme, called EasiRA, for 802.11 mobile wireless access networks. It has following three features. First, it combines the sensor-hints and protocol-hints information together to estimate current link status. Second, EasiRA exploits environmental signal strength information obtained by a 802.15.4-based radio to help distinguish the causes of packet losses and adjust the thresholds of the protocol-hints. Finally, EasiRA uses both random and deterministic rate increase or decrease schemes to combat the dynamic and unpredictable characteristics of wireless links. Simulation results show that EasiRA consistently outperforms the existing rate adaptation schemes, namely CARA, Minstrel and RapidSample, particularly in relatively high dynamic scenario.**

I. Introduction

With the proliferation of Internet of Things (IoT) [1], more and more devices with varying mobility supports, such as mobile phones, PDAs, embedded networked sensing nodes, or automobiles, are to be connected with each other to exchange information. It is more feasible and flexible to make them connected through accessing to the Internet via wireless access networks, such as 802.11 networks. However, the increasing mobile devices lead to high dynamic and congested wireless links, which adversely affect the performance of wireless access networks. Since their performance determines the scale of IoT and future Internet, a lot of schemes have been proposed to enhance the performance of wireless access networks. Bit rate adaptation is one of these schemes. It selects appropriate bit rates according to current link conditions by promptly adjusting modulation and coding schemes. An efficient rate adaptation scheme must be able to address the following two critical challenges in mobile and congested environments.

- Obtaining link status information quickly and accurately. Because stale or inaccurate link quality information causes frequent over-selection or under-selection of bit rates, and networks cannot make full use of the limited bandwidth resources.
- Identifying the causes of packet losses. There are mainly two kinds of packet losses in wireless networks: channel-error induced and collision induced packet losses. The former is caused by weak signal due to signal attenuation, channel fading or multi-path fading. While the latter is caused by signal collision of multiple concurrent transmissions. An efficient rate adaptation algorithm must be able to distinguish the above two cases, because reducing bit rates in response to collisions will increase the duration of packet transmission and will exacerbate collisions [2].

Taking the above challenges into account, we introduce a hybrid rate adaptation scheme, called EasiRA, for 802.11 mobile wireless access networks. EasiRA has the following three salient features.

First, EasiRA combines two kinds of information together to accurately measure the current link quality. On one hand, like many traditional rate adaptation algorithms, EasiRA takes the counts of consecutive packet transmission successes or failures (protocol-hints). On the other hand, EasiRA uses sensor-hints information obtained from sensors equipped by most current mobile devices [3], like node's movement speed from accelerometers and location from GPS, to guide the link quality estimation.

Second, EasiRA uses a low power radio, such as 802.15.4-based radio to obtain timely environmental signal strength (ESS) information to help differentiate the causes of packet losses. This function can be realized in real networks because recent researchers have developed devices equipped by multiple radios which can work under different standards [4]. Furthermore, EasiRA also adopts an adaptive protocol-hints threshold mechanism based on ESS estimates to combat the variations of wireless link state.

Finally, EasiRA combines random and deterministic rate selection methods together to cope with the unpredictable changes of wireless link status.

We conduct extensive simulations to evaluate the performance of EasiRA via ns-3 network simulator. Our simulation results show that EasiRA achieves gains of 8% over CARA, 31.8% over Minstrel and 46% over RapidSample respectively in relatively high dynamic scenario.

The rest of the paper is organized as follows. Section II gives an overview of related work on rate adaptation. Section III describes the design and implementation of the proposed rate adaptation scheme EasiRA. Performance evaluation based on simulation is presented in Section IV. Section V concludes the paper.

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II. Related work

A large quantity of research work on rate adaptation have been published in the literature. They can be generally classified into the following three categories.

Frame-based: Frame-based rate adaptation schemes use either consecutive packet transmission successes or failures, or packet delivery ratios in a time window, to sequentially increase or decrease bit rates. AARF [5], SampleRate [6] and Minstrel [7] are collision-ignored and reduce bit rates once packet loss occurs. CARA [8] and RRAA [9] are collision-aware and use adaptive RTS/CTS exchanges to distinguish the causes of packet losses. Frame-based ones are in nature not responsive to variations of link status, because they require multiple frame transmissions to converge to a meaningful estimated value of link status. In addition, they usually adopt the fixed threshold mechanism (e.g., 10 consecutive successes or 1 failure) to adjust the bit rate, which cannot work well in different environments.

SNR-based: SNR-based rate adaptation schemes use the timely collected SNR value to select an appropriate bit rate through looking up a predefined SNR-rate table. RBAR [10], OAR [11], CHARM [12], FARA [13], RAM [14] and ESNR [15] belong to this category. Compared with frame-based ones, the SNR-based ones react more quickly to the changes of link status. However, it is difficult to obtain the accurate SNR values, and capture the exact SNR-BER relationship in different propagation environments, especially in mobile environments.

PHY-based: PHY-based rate adaptation schemes exploit physical layer information directly to select bit rates. The most recent ones include SoftRate [16], AccuRate [17] and Strider [18]. PHY-based schemes are in nature responsive to the variations of link status. However, they require to modify the physical layer, which are hard to be implemented on recent commercial wireless devices.

To overcome the limitations of existing rate adaptation schemes, we design EasiRA to improve the performance of rate adaptation scheme by making a tradeoff between accuracy and speed of reaction to the variations of link status.

The closest proposal to EasiRA is the one presented in the paper [3], which uses device's state of motion gained by sensors to select different rate adaptation schemes for static and mobile environments. In detail, it selects RapidSample when a node is moving, and SampleRate when a node is static. EasiRA is different from RapidSample in that it uses node's moving speed and location directly to guide the process of rate selection. In addition, RapidSample does not differentiate the causes of packet losses, so it underperforms in mobile and congested scenarios as shown in our simulation studies.

III. Design of EasiRA

In this section, we present the design details of EasiRA.

A. Overview of EasiRA

EasiRA consists of two key components: link status sensor (LSS) and rate selection controller (RSC). Figure 1 shows the overall structure of EasiRA.

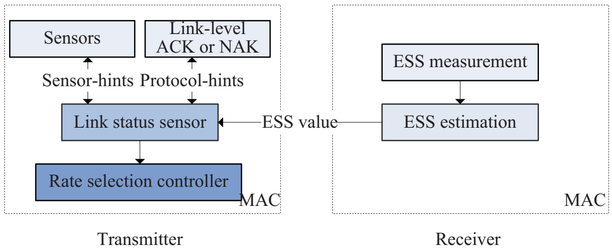


Fig. 1. Modules and interactions in EasiRA

LSS: LSS is mainly responsible for collecting timely information about link status, which not only includes the consecutive packet transmission successes or failures (protocol-hints), but also the node's current position and movement speed (sensor-hints). Meanwhile, LSS uses estimated ESS information to improve the accuracy of link status estimation. ESS estimation module controls the process of link status estimation in return, such as the size of time window. Another important function of LSS is to differentiate the causes of packet losses with the help of instant ESS observations. LSS is supposed to run in the transmitter and receiver together to achieve the above goals.

The intuition behind LSS lies in the following fact. When two nodes get closer to each other, the link quality between them will be getting better with high probability. In contrast, when a node moves with high speed, the link status will change more quickly and the probability of collision-induced packet loss will be low. Therefore, it is beneficial to use sensor-hints as an assistant of LSS to estimate the changing trend of link status. Moreover, the instant sensor-hints can compensate for the slow convergence of protocol-hints, and estimate link status timely and accurately.

RSC: RSC selects an appropriate bit rate based on the link quality estimated by LSS. EasiRA adopts both the random and deterministic rate adaptation methods. Specifically, when a node has high confidence that the link will become better or worse, then it deterministically picks next higher or lower rates. Otherwise, the node will randomly chooses a rate from predetermined rate sets with a certain probability.

B. Link status sensor

For the LSS of EasiRA, the novelty is mainly embodied in its adoption of sensor-hints and ESS for distinguishing causes of packet losses and adapting the thresholds of protocol-hints. Here, we will describe them in detail.

1) ***Distinguishing causes of packet losses***: We set up an experiment to demonstrate how the ESS value varies with the time. Here, the ESS is different from the received signal strength (RSS), in that the latter is computed only when a packet is successfully received, while the former is directly read from a register of the radio no matter whether there is packet arriving. The experiment is set up as follows. Two laptops transmit packets to another laptop every one millisecond simultaneously. At the same time, we put a sensor node equipped with an 802.15.4-based radio at the receiver side to read the ESS value every one millisecond. We repeat

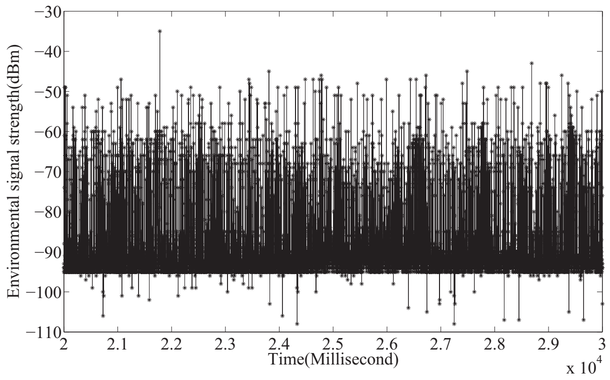


Fig. 2. Environmental signal strength obtained from 802.15.4-based radio

the experiments in different environments and time of a day. Figure 2 shows the variations of ESS value over the time in the building of our laboratory. From these experimental results, we can find there are some spikes of ESS value, for example, which is greater than -50dBm or less than -95dBm. In these cases, the packet losses are caused by collisions with high probability. Thus, we use these information as guidance to identify the causes of packet losses.

Accordingly, we define two parameters $\mathrm{ESS_{up}}$ and $\mathrm{ESS_{down}}$. When the ESS value is less than $\mathrm{ESS_{down}}$ or greater than $\mathrm{ESS_{up}}$, we infer that a collision occurs possibly. The values of $\mathrm{ESS_{up}}$ and $\mathrm{ESS_{down}}$ are determined according to the propagation environment and hardware equipped with the node. Besides that, we make use of the sensor-hints to further confirm that it is collision not weak signal that causes the packet loss. When the two nodes approach each other and the movement speed is below a certain threshold $\mathrm{speed_{high}}$, then we can predict that the probability of collision occurrence is very high. We modify the interference module in the ns-3 to implement this function.

So, in order to differentiate the causes of packet losses, the transmitter and receiver need to work cooperatively. The receiver must feed back the changes of ESS value to the transmitter promptly. We implement this function based on the package of 802.11a protocol in the ns-3. Since only a positive acknowledge frame (ACK) will be sent back to the transmitter by default in the 802.11 standard when a packet is successfully received, there is no information conveyed explicitly to the transmitter when a packet is lost. To achieve this target, we defined another MAC-level control frame, named non-acknowledgement (NAK). Specifically, when a packet cannot be received successfully due to bit errors, and the ESS value is less than $\mathrm{ESS_{down}}$ or greater than $\mathrm{ESS_{up}}$, the receiver sends back a NAK frame to explicitly inform the transmitter that it may suffer collision. If the transmitter has neither received ACK nor NAK, then it infers that channel-error induced packet loss has occurred and should reduce to a lower rate. The format of NAK is defined as the same with ACK.

2) ***Adapting thresholds of protocol-hints***: EasiRA defines two thresholds for protocol-hints, namely α and β. When more than α packets have been continuously successfully transmitted, the transmitter picks a higher bit rate at the next round of packet transmission. Otherwise, if more than β packets have been lost consecutively, the transmitter selects a lower bit rate. It is inefficient to set these two thresholds fixed, because a larger α or a smaller β value may result in frequent under-selection or over-selection of bit rates in mobile environments, especially when the link status becomes good or bad suddenly but only lasts for a short time. Furthermore, smaller α or β value may lead to vibration of bit rate adaptation when the link status changes quickly. Therefore, the fixed protocol-hints thresholds cannot adapt to different environments. To solve this problem, EasiRA introduces an adaptive mechanism to adjust the thresholds of the protocol-hints. Specifically, the two thresholds are adapted on-line based on the ESS estimation information obtained from the receiver.

Because the ESS value is affected by the hardware and propagation environments [19], an individual ESS value cannot accurately reflect the real link state. In our paper, we design a conservative ESS estimation method to deal with the ESS fluctuation problem using the error-based filter (EF) [20], which is formulated as follows.

$$ESS_t = \gamma ESS_{t-1} + (1-\gamma) ESS_{current}, \qquad (1)$$

where ESS_t is the current estimate of ESS, ESS_{t-1} is the prior estimate of ESS, and $ESS_{current}$ is the current observation of ESS. The γ is the smoothing factor, which is not constant and calculated by the following equation.

$$\gamma = 1 - \frac{\delta_t}{\delta_{max}}, \qquad (2)$$

where δ_t is the predictive power of the EF estimator, which can be adapted to control the error deviation of the EF estimator. So δ_t is also named as estimator error. When the EF estimator produces estimates that match well with reality, it gives more weight to the prior estimates through increasing the smoothing factor γ, otherwise, it reduces the weight of the prior estimates by decreasing the smoothing factor. The estimate error δ_t is the absolute difference between the prior estimate and the current observation. Rather than uses the raw error directly, the EF estimator uses a secondary exponentially weighted moving average (EWMA) filter to smooth the estimate error δ_t:

$$\delta_t = \lambda \delta_{t-1} + (1-\lambda) |ESS_{t-1} - ESS_{current}|. \qquad (3)$$

δ_{max} is the largest estimate error of the most recent measurements. λ is 0.7 and is chosen empirically to minimize the estimation error under the network scenarios presented in section IV. The receiver sends back the ESS estimate value ESS_t to the transmitter via transmitting the ACK at a variable rate, like the approach presented in [14]. Specially, if the ESS_t is above a certain threshold $\mathrm{ESS_{good}}$, then it sends the ACK at a higher bit rate to notify the transmitter to reduce the α and increase the β and jump to a higher bit rate directly. Otherwise, it transmits the ACK at a lower bit rate to notify the transmitter to increase the α and decrease the β. Therefore, there are two categories of thresholds for the protocol-hints: α_{large}, α_{small} and β_{large}, β_{small}. In performance evaluation,

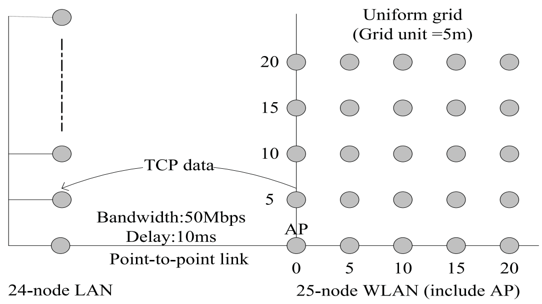


Fig. 3. Initial simulation topology

these parameters are set to 10, 5, 2 and 1 respectively under which EasiRA yields better performance.

C. Rate selection controller

Based on link status information provided by the LSS, the RSC decides when to increase or decrease rate so as to maximize the throughput of the mobile access networks. Different from most of the existing rate adaptation schemes, which decrease to a lower bit rate or increase to a higher bit rate, or directly select an optimal bit rate deterministically, RSC combines the random and deterministic rate adaptation mechanisms together to cope with the dynamic and unpredictable characteristics of the wireless links, especially in the mobile environment with relative high dynamics. The pseudo code to implement the RSC is shown in Algorithm 1. It starts with a bit rate randomly selected from the available rate sets with same probability as shown in line 3 of Algorithm 1. Here, the ESS_t is computed using EF estimator only when a packet is received. In other words, we filter the ESS observations out when there are no successful packet transmissions. Meanwhile, the $ESS_{instant}$ is measured periodically all the time. $isApproaching$ is a boolean variable, which is set to true when the mobile station is moving toward the AP.

IV. Performance evaluation

In this section, we present the results of performance evaluation.

A. Simulation setup

We implement EasiRA and RapidSample in ns-3 network simulator, which provides a realistic frame error rate model for different modulation and coding schemes and an accurate wireless channel model for different propagation environments. We create a scenario composed of an infrastructure basic service set (BSS) with a fixed access point (AP) and 24 mobile stations. The AP is connected to a 24-node local area network via a point-to-point link. We establish 24 TCP connections from WLAN stations to LAN nodes. The initial simulation topology is shown in Figure 3. Table I and II summarize the configuration parameters and their settings in our simulations. We consider two mobile scenarios, where the speed of movement is uniformly distributed in [1, 10] and [10, 20] respectively.

We compare the performance of EasiRA against the following four rate adaptation algorithms. The Ideal algorithm

Algorithm 1 Bit Rate Selection Algorithm

Input:

α_{small}, α_{large}, β_{small}, β_{large}, ESS_t, $ESS_{instant}$, ESS_{good}, $\text{speed}_{\text{high}}$, $isApproaching$;

Output:

Bit rate br;

1: $\alpha \leftarrow \alpha_{\text{small}}$, $\beta \leftarrow \beta_{\text{large}}$;
2: $isCollision \leftarrow$ false;
3: $br \leftarrow$ Uniform(br_{min},br_{max});
4: **if** (ACK) **then**
5:   $success \leftarrow success + 1$;
6:   $failure \leftarrow 0$;
7:   $isCollision \leftarrow$ false;
8:   **if** $ESS_t \geq ESS_{good}$ && $isApproaching$ **then**
9:     $success \leftarrow 0$;
10:     $br \leftarrow$ Uniform(br+1,br_{max});
11:     $\alpha \leftarrow \alpha_{\text{small}}$, $\beta \leftarrow \beta_{\text{large}}$;
12:   **else**
13:     **if** $success \geq \alpha$ **then**
14:       $success \leftarrow 0$;
15:       $br \leftarrow br + 1$;
16:       $\alpha \leftarrow \alpha_{\text{large}}$, $\beta \leftarrow \beta_{\text{small}}$;
17:     **end if**
18:   **end if**
19: **else**
20:   **if** (NAK) **then**
21:     **if** $speed \leq \text{speed}_{\text{high}}$ && $isApproaching$ **then**
22:       $isCollision \leftarrow$ true;
23:     **end if**
24:   **end if**
25:   $failure \leftarrow failure + 1$;
26:   $success \leftarrow 0$;
27:   **if** $failure \geq \beta$ **then**
28:     $failure \leftarrow 0$;
29:     **if** !$isCollision$ **then**
30:       $br \leftarrow br - 1$;
31:     **else**
32:       $br \leftarrow$ Uniform(br_{min}, br);
33:     **end if**
34:   **end if**
35: **end if**
36: **return** br;

TABLE I
Simulation parameters and their settings in our experiments

Parameters	value
Physical standard	802.11a
MAC protocol	CSMA/CA
Link layer queue length	1200
Packets size/numbers	1024bytes/1200packets
Mobility model	RandomDirectional2dMobilityModel
Mobility speed	Uniform(1,10)/(10,20)(mps)
Application traffic type/rate	TCP/1Mbps
Simulation topology	Rectangle range:(-100,100,-100,100)(m)
Experiment times for every value	5

TABLE II

BIT RATES SUPPORTED IN 802.11A STANDARD AND ITS CORRESPONDING SNR THRESHOLD TAKEN IN OUR CONFIGURATIONS(BER=10E-6)

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

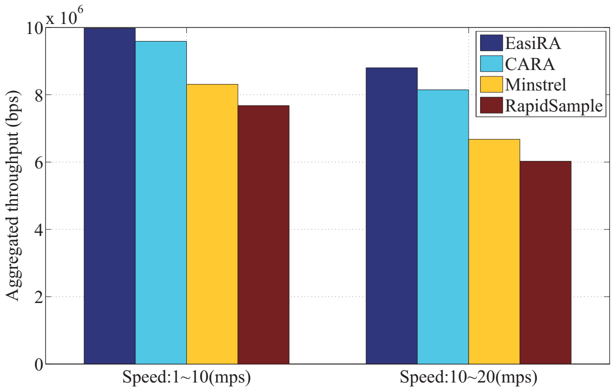


Fig. 4. Aggregated throughput achieved by EasiRA, CARA, Minstrel and RapidSample

is taken as the benchmark of our evaluations. CARA [8], Minstrel [7] and Ideal are released as a part of ns-3 simulator. Features of these schemes are summarized as follows.

- RapidSample [3]. The first algorithm which introduces sensor-hints to rate adaptation. It is frame-based and collision-ignored.
- Minstrel. It is claimed to be one of the best rate selection algorithm that is widely used in the MadWifi driver. It is frame-based and collision-ignored.
- CARA. A frame-based and collision-aware rate adaptation algorithm, which achieves almost the best performance out of all the existing frame-based algorithms.
- Ideal. It is SNR-based and similar to RBAR [10] in spirit.

B. Simulation results

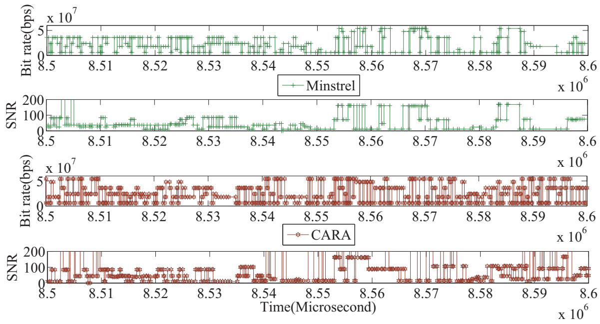
Results: Figure 4 shows the aggregated throughput achieved by EasiRA, CARA, Minstrel and RapidSample. As shown in that figure, all the algorithms suffer throughput degradation when the node's speed increases, which are 11.8%, 15%, 19.6% and 21.5% for EasiRA, CARA, Minstrel and RapidSample respectively. However, EasiRA works best, and RapidSample performs worst in both environments. Table III gives the ratio of aggregated throughput of EasiRA, Minstrel, CARA and RapidSample to that of Ideal.

To get a deep understanding of how these rate control algorithms work in highly dynamic environment, we dump the trace of chosen bit rates and SNR value variations over time in simulations. Due to the space limitation, we only plot the

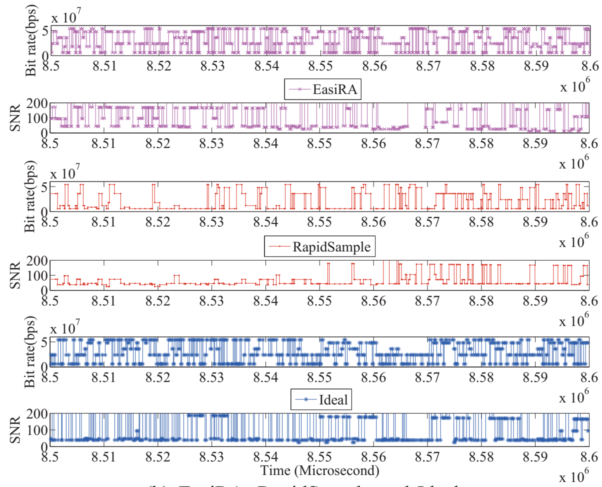
TABLE III

AGGREGATED THROUGHPUT RATIO OF EASIRA, CARA, MINSTREL AND RAPIDSAMPLE TO IDEAL'S

Scenarios	EasiRA	CARA	Minstrel	RapidSample
Speed:1∼10	86.1%	82.7%	71.7%	66.3%
Speed:10∼20	86.2%	79.9%	65.4%	59.1%



(a) Minstrel and CARA

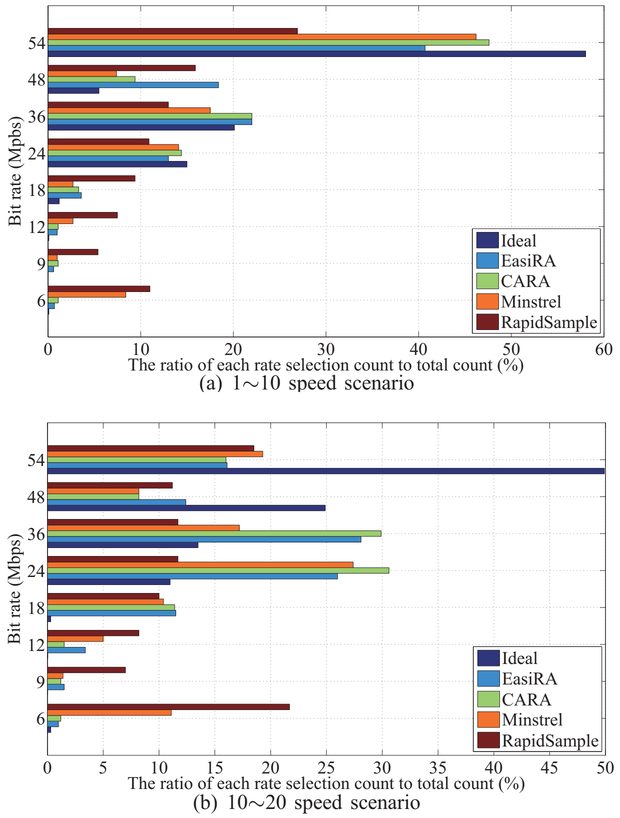


(b) EasiRA, RapidSample and Ideal

Fig. 5. Instant rate and SNR over time for all algorithms

results obtained from 10∼20 speed scenario and the SNR values that are greater than 200 were not displayed in figures. All algorithms get similar results in 1∼10 speed scenario. From Figure 5, we can find that EasiRA acts more closely to Ideal than CARA, Minstrel and RapidSample. This is attributed to the sensor-hints and ESS guided rate adaptation scheme adopted by EasiRA, which makes EasiRA robust to collision-induced packet losses and react rapidly and accurately to the variations of link conditions. RapidSample reacts to packet losses too aggressively which results in frequent rate changes but mismatch with link conditions. Compared with Minstrel and RapidSample, CARA achieves a good performance close to EasiRA, this is because its aggressively adaptive RTS/CTS exchanging mechanism suppresses the collisions and it opportunistically chooses a high bit rate to transmit packets.

The above results are further confirmed by the statistics shown in Figure 6, which shows the ratio of selection count of each rate to the total counts for all the algorithms in two scenarios. Particularly, in 1∼10 and 10∼20 speed scenarios, EasiRA has 40.7% and 16.1% packets transmit at the rate of



(a) 1∼10 speed scenario

(b) 10∼20 speed scenario

Fig. 6. Ratio of selection counts of each rate to total count achieved by all algorithms

54 Mbps respectively. EasiRA and CARA tend to select more higher bit rates as Ideal algorithm does. This further confirms that the LSS and RSC modules of EasiRA work effectively in mobile and congested environments.

Implications: Collision identification and rapid reaction to link dynamics are two critical problems that the rate adaptation scheme must resolve. Using RTS/CTS exchanges to cope with the problem of collision identification incurs additional control overhead. Although EasiRA is coarse-grained to identify collisions using external information, such as sensor-hints and ESS, it works efficiently.

V. Conclusion and Future Work

In this paper, we have presented EasiRA, a hybrid rate adaptation scheme for 802.11 mobile wireless access networks. Its core idea is to exploit the sensor-hints and ESS information to guide the link status estimation and collision identification. Meanwhile, EasiRA combines random and deterministic rate selection schemes together to deal with the dynamic and unpredictable characteristics of wireless links. Simulation results show that EasiRA is robust to collision-induced packet losses and reacts quickly to the variations of link status. It consistently outperforms the existing frame-based rate adaptation schemes CARA, Minstrel and RapidSample in both 1∼10 and 10∼20 speed scenarios. In the latter scenario, it improves throughput by up to 8% over CARA, 31.8% over Minstrel and 46% over RapidSample respectively.

In terms of future work, we will implement EasiRA on our testbed EZ270 [4] and evaluate its performance in real environment. In addition, we will take the energy consumption into consideration.

Acknowledgement

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