SIRA: SNR-aware Intra-frame Rate Adaptation

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Abstract—An intra-frame rate control algorithm (Intra-RCA), called SNR-aware Intra-frame Rate Adaption (SIRA), is proposed to enhance the system performance of WiFi in fast time-varying environments. Widely used inter-frame rate control algorithms (Inter-RCA), which select the physical layer (PHY) rate of each frame based on the time averaged frame loss rate and the signal strength statistics, perform poorly for a long aggregate MAC protocol data unit (A-MPDU) due to the channel variation in mobile environments. Unlike the previous approaches, SIRA adapts the PHY rate on intra-frame basis, i.e., the PHY rate is updated in the middle of a frame according to user mobility. The performance of the proposed scheme is also evaluated by a trace-driven link level simulator employing the collected channel traces from real measurements. The simulation results show that SIRA outperforms the standalone Inter-RCA in all tested traces.

Index Terms—Mobility, A-MPDU, Rate control, IEEE 802.11n

I. INTRODUCTION

RECENTLY, WiFi, wireless local area network (WLAN) technology based on IEEE 802.11, has been spotlighted as one of promising wireless network technologies. With the ever-increasing demand for high-throughput WLANs, IEEE-802.11 have allowed higher physical layer (PHY) rates and added MAC protocol/service data unit (MPDU/MSDU) aggregation mechanisms [1]. The improvement in throughput and efficiency leads to significant growth in the take-up of WiFi equipped mobile devices, such as smartphone, tablet, and wearable devices. Accordingly, handling the mobility for the emerging WiFi devices becomes increasingly important.

Rate adaptation is one of the key technologies to reflect the impact of user mobility. The well-known rate adaptation schemes, ARF and CARA, make rate decision based on frame loss statistics, but their adaptation speed is slow [2]. Other algorithms such as SGRA and AccuRate [3, 4] utilize PHY information, such as signal-to-noise ratio (SNR) and symbol dispersion, to improve the responsiveness and accuracy, respectively. All these algorithms are inter-frame rate control algorithms (Inter-RCAs) that assume wireless channel to be invariant throughout one frame duration, thus the same modulation and coding scheme (MCS) is used within a frame.

However, the assumption of quasi-stationary channel over one frame duration is proved to be invalid, since the state-of-the-art WiFi devices commonly employ long aggregate MPDU (A-MPDU) frames. A-MPDU unfetters the repressed PHY rate originated from MAC/PHY overhead by amortizing the overhead over multiple MPDUs aggregated in a single frame. Nevertheless, A-MPDU requires long frame duration, e.g., the maximum 10 ms, which exceeds the coherence time frequently in mobile environments. Our experimental results confirm that the use of A-MPDU aggravates reception capability for mobile users, even if an appropriate PHY rate is chosen by Inter-RCA.

In this paper, we propose SNR-aware Intra-frame Rate Adaptation Algorithm (SIRA) which allows the transceivers to effectively adapt the PHY rates within an individual frame. SIRA defines and uses the primary-secondary MCS pairs adaptively for a specific frame when user mobility is detected based on the PHY information. We further minimize the feedback overhead via zero-overhead feedback to notify the presence of user mobility from the receiver to the sender.

II. MOTIVATION

Impact of mobility: In order to verify the impact of user mobility on A-MPDU, we have conducted experiments using two popular 802.11n network interface cards (NICs) in an indoor office. We install stations equipped with Atheros 9380 (AR9380) or Intel WiFi Link 5300 (IWL5300) chipset, which support A-MPDU [5, 6]. Meanwhile, an access point (AP) mounts AR9380. Our testbed operates on the 5.22 GHz channel in a controlled environment; no interference is observed. The AP transmits saturated traffic to the stations which come and go between two positions (located at 1 m and 5 m away from the AP, respectively) at an approximately constant, pedestrian speed of 0.5 m/s or 1 m/s. We enable A-MPDU and use the optimal fixed MCS 7 (65 Mb/s) chosen by inter-RCA in static environments.

Fig. 1(a) shows that the subframes located at the latter part of the A-MPDU suffer from high subframe error rate (SFER). The slope of the curves becomes higher as the speed of the station increases regardless of the NIC type. In other words, even if the A-MPDU is transmitted at the appropriate PHY rate, the A-MPDU experiences subframe losses, and the loss rate is proportional to the degree of mobility. We call such losses causal losses.

Limitation of IEEE 802.11: A-MPDU experiences the caudal losses due to the limited channel compensation procedure of IEEE 802.11. The IEEE 802.11n receiver estimates the channel state information (CSI) by using the long training field (LTF) of the preamble to compensate the distortion of data OFDM symbols induced by fading, shadowing, and so on. However, the estimated CSI is not adequate for compensating the data symbols located at the latter part of A-MPDU, because the channel dramatically changes within one A-MPDU duration in mobile environments. Accordingly, the compensated symbols get dispersed from their ideal positions in I-Q plane regardless of the received signal strength (RSS) and the moving direction. For example, even when the receiver gets closer to the transmitter, the caudal losses are observed.

To demonstrate this phenomenon, we have developed a trace-driven link level simulator described in Section IV. Figs. 1(b) and 1(c) show the amount of symbol dispersion, i.e.,
error vector magnitude (EVM), in mobile traces. As shown in Fig. 1(b), EVM increases as the OFDM symbol index increases, and the increasing rate of EVM becomes higher as the speed of the station increases. In low RSS region, the overall EVM is increased while the slope remains the same regardless of RSS. Fig. 1(c) shows the received symbol positions derotated by CSI from LTF when the station moves at the speed of 1 m/s. The symbol dispersion at the latter part of the A-MPDU is much larger than that at the front part of the A-MPDU, and hence, the asymmetric dispersion leads to caudal losses.

According to the IEEE 802.11 standard, four pilot subcarriers are evenly spaced in the middle of data subcarriers to eliminate phase offset as time goes during the frame reception. However, the pilots are inappropriate to estimate the CSI of the whole bandwidth as the pilot spacing is much larger than the coherence bandwidth [7]. In other words, pilots compensate the phase offset not caused by channel variation but by the clock mismatch between the transmitter and receiver. Thus, when A-MPDU is used in mobile environments, the conventional 802.11 protocol might not guarantee the successful reception of the subframes at the latter part.

**Channel and mobility condition:** The caudal losses are not originated by fading, shadowing, and the noise of the RF hardware (channel condition), but by the gap between the CSI from the preamble and time-variant channel (mobility condition). We believe that it is important to differentiate channel condition from mobility condition. Since the existing algorithms have considered only the channel condition, we propose more sophisticated rate adaptation algorithms utilizing the mobility condition for WiFi mobile devices.

### III. Proposed Algorithm

The proposed rate adaptation algorithm, SIRA, consists of four procedures: (1) pilot-based SNR estimation, (2) unequal MCS, (3) mobility detection, and (4) zero-overhead feedback.

#### A. Pilot-based SNR estimation

In developing an algorithm which quickly adapts the PHY rate by considering mobility condition, two issues must be addressed: the differentiation of the loss caused by the mobility condition from the loss caused by the channel condition, and the determination of the starting point, \( I_U \), where the OFDM symbols begin to suffer severe BER due to the inaccurate CSI. To solve these issues, we use the estimated SNR obtained by PHY information, i.e., EVM, as the root mean squared value of the difference between the received symbol \( S_r \) and the corresponding transmitted symbol \( S_t \). Using the relationship between SNR and \( \text{EVM}_{\text{rms}} \), if the number of the received symbols \( N \) is large, SNR can be obtained as follows [8]:

\[
\text{SNR} = \frac{E_s}{N_0} \approx \frac{1}{\text{EVM}^2_{\text{rms}}} = \frac{1}{N} \sum_{n=1}^{N} |S_t(n)|^2 \frac{1}{N} \sum_{n=1}^{N} |S_r(n) - S_t(n)|^2,
\]

where \( N_0/2 \) is the noise power spectral density and \( E_s \) is the average symbol energy.

Since it is difficult to obtain \( \text{EVM}_{\text{rms}} \) from unknown data symbols, we exploit the known pilot symbol sequence. However, each OFDM symbol has very small number of pilots, i.e., the number of pilots per an OFDM symbol, \( N_p \), is 4 or 6 for 20 or 40 MHz channel bandwidth, respectively. Thus, we group \( N_i \) pilots corresponding to \( N_S \) OFDM symbols into a received pilot group, \( P_i^{\text{tx}} = [p_i^{\text{tx}1}, p_i^{\text{tx}2}, \ldots, p_i^{\text{tx}N_S}] \), \( N_i = N_S \times N_p \). Let \( p_{ij}^{\text{rx}} \) be the \( j \)th pilot sample in the \( i \)th received pilot group \( P_i^{\text{rx}} \) corresponding to the \( j \)th transmitted pilot group, \( P_i^{\text{tx}} \). The receiver then estimates \( \text{SNR}_i \) based on Eq. (1), for each group \( i \) of symbols:

\[
\text{SNR}_i = \frac{E_s}{N_0} \sum_{i=1}^{K} \frac{1}{N_i} \sum_{j=1}^{N_i} \left| p_{ij}^{\text{rx}} - p_{ij}^{\text{tx}} \right|^2,
\]

where \( K \) is the number of pilot groups in an A-MPDU.

\( \text{SNR}_i \) is proportional to the accuracy of CSI which is defined as the similarity between the CSI from LTF and the channel response experienced by the group \( i \). For example, \( \text{SNR}_1 \) is very high for perfect CSI. Based on the SNR distribution, \( \text{SNR} = [\text{SNR}_1, \text{SNR}_2, \ldots, \text{SNR}_K] \), the mobility detection and the determination of \( I_U \) are performed.

#### B. Mobility detection

Using the SNR distribution, SIRA decides the presence of the mobility at the receiver side. In mobile environments, the accuracy of CSI and SNR monotonically decrease during a frame reception due to the fact that the human mobility pattern does not change significantly within a single A-MPDU duration (e.g., 10 ms, the maximum frame duration [1]). Otherwise, the accuracy and SNR slightly fluctuate in static conditions.
environments. As the evidence, Fig. 1(b) shows that the average EVM monotonically increases as the OFDM symbol index increases in mobile traces, whereas it remains steady in static trace. Based on this observation, we suggest that the detection of mobility can be determined by testing the monotonicity of SNR. If the estimated SNR decreases with the increase of symbol index, SIRA concludes that the station is under a mobile environment.

C. Unequal modulation and coding scheme

SIRA employs unequal MCS (UEQ-MCS) which allows the use of multiple MCSs for a given frame. We define 8 pairs of primary and secondary MCSs for UEQ-MCS as shown in Table I. UEQ-MCS encodes and modulates the data messages using primary MCS with rate $R_p$ until the OFDM symbol index $I_U$ from which the data symbol suffer from inaccurate CSI. The corresponding secondary MCS with rate $R_s$ is used for the residual OFDM symbols only when mobility is detected according to Section III-B. Note that $R_p$ is selected by Inter-RCA which only considers the channel condition, and $R_s$ is defined to be the highest MCS that uses one-step lower modulation and less than or equal to the coding rate of $R_p$, as shown in Table I. The key challenge of UEQ-MCS is how to determine $I_U$.

**Algorithm 1: $I_U$ decision pseudo code.**

```plaintext
Data: SNR, SNRth, Rp
if SNR is monotonically decreasing then
    for i ← 1 to K do
        if SNR < SNRth (Rp) then
            $I_U$ ← $i \times N_S$;
            Feedback $I_U$
        end
    end
end
```

As illustrated in Algorithm 1, if the SNR monotonically decreases, SIRA tries to find the first $I_U$ from the beginning of the frame that satisfies the condition $\text{SNR}_i < \text{SNR}_{th}(R_p)$. We define $\text{SNR}_{th}$ as the minimum SNR at which the theoretical coded BER of $R_p$ is less than roughly $10^{-4}$ based on the most popular error rate model [9]. The receiver then feedbacks $I_U$ to the transmitter by using zero-overhead feedback protocol described in the following section. Based on the feedback value of $I_U$, the transmitter can prepare the next A-MPDU data frame by selecting the appropriate primary-secondary MCS pair. Table I summarizes the primary-secondary MCS pairs and the corresponding SNRth.

UEQ-MCS is easy to implement in practice. Note that the baseline 802.11 WLAN already uses two different MCSs for a single frame. That is, data OFDM symbols are transmitted with the best MCS chosen by Inter-RCA while the signal fields of the preamble, i.e., L-SIG and HT-SIG, are transmitted with BPSK and 1/2 coding rate. Similarly, SIRA uses $R_p$ for the data OFDM symbols whose indices are smaller than $I_U$, while the rest are encoded/modulated with $R_s$.

**TABLE I: Primary-secondary MCS pairs and SNR thresholds.**

<table>
<thead>
<tr>
<th>$R_p$</th>
<th>$R_s$</th>
<th>SNRth (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCS 0</td>
<td>BPSK, 1/2</td>
<td>MCS 0</td>
</tr>
<tr>
<td>MCS 1</td>
<td>QPSK, 1/2</td>
<td>MCS 0</td>
</tr>
<tr>
<td>MCS 2</td>
<td>QPSK, 3/4</td>
<td>MCS 0</td>
</tr>
<tr>
<td>MCS 3</td>
<td>16QAM, 1/2</td>
<td>MCS 1</td>
</tr>
<tr>
<td>MCS 4</td>
<td>16QAM, 3/4</td>
<td>MCS 2</td>
</tr>
<tr>
<td>MCS 5</td>
<td>64QAM, 2/3</td>
<td>MCS 3</td>
</tr>
<tr>
<td>MCS 6</td>
<td>64QAM, 3/4</td>
<td>MCS 4</td>
</tr>
<tr>
<td>MCS 7</td>
<td>64QAM, 5/6</td>
<td>MCS 4</td>
</tr>
</tbody>
</table>

D. Zero-overhead feedback

The requirement of the feedback information $I_U$ from receiver to transmitter in SIRA imposes undesirable overhead. To avoid the undesirable overhead, we introduce zero-overhead feedback protocol, which is the same technique used in the high throughput signal field (HT-SIG). HT-SIG provides not only the explicit information (e.g., MCS, length and so on) by using bit stream but also the implicit information whether the frame is HT format by using $90^\circ$ rotated constellation relative to BPSK. Similarly, SIRA piggybacks $I_U$ in BlockAck (Block Acknowledgment). Let $P_{i,j}$ denotes the $j^{th}$ pilot symbol on OFDM symbol $i$. The pilot symbols can be substituted for $90^\circ$ rotated symbols, $\tilde{P}_{i,j}$, for piggybacking as follows:

$$\tilde{P}_{i,j} = \varphi_k \times P_{i,j},$$

s.t. $\varphi_k = \begin{cases} e^{j2\pi i/N_p}, & \text{if } b_k = 1, \\ e^{j0}, & \text{if } b_k = 0, \end{cases}$

$$i = \left[ k/N_p \right], \quad j = k \mod N_p,$$  

(3)
where \( b = [b_0, b_1, \cdots] \) is the binary representation of \( I_U \). \( b_0 \) is used for the signature of whether the BlockAck carries the piggyback information. The receiver can extract \( \varphi_k \) by comparing the known pilot sequence, \( P_{i,j} \) with the received pilot symbol of the previous symbol, \( P_{i-1,j} \), before pilot-based phase offset tracking. It is obvious that the feedback does not aggravate the performance of the phase offset tracking.

An example of SIRA operation is described in Fig. 2. The transmitter first sends the A-MPDU with the primary MCS 7 over the mobile channel. Based on the SIRA algorithm, the receiver detects mobility and finds the first group of symbols \( M \) which meets the condition \( \text{SNR}_M < \text{SNR}_{th}(\text{MCS 7}) \). The receiver then informs \( I_U = M \times N_S \) to the transmitter via zero-overhead feedback. Finally, the next A-MPDU is modulated and coded unequally using the primary-secondary MCS pair.

IV. PERFORMANCE EVALUATION

We have implemented a trace-driven link level simulator, where IEEE 802.11n PHY/MAC layer protocol stacks are implemented based on GNU Radio and IT++ libraries [10, 11] and the fine-grained channel traces are measured for 30 subcarrier groups using IWL5300 NIC and the 802.11n CSI tool introduced in [12]. We collect 14 channel traces with various degrees of mobility at different locations, and each trace contains 40,000 CSIs. The measured CSIs are interpolated over 56 subcarriers. The channel model in the simulator is replaced by the collected traces. We also have implemented SGRA, one of the best inter-RCAs for comparison purpose.

We first evaluate the accuracy of mobility detection and \( I_U \) prediction. SIRA achieves over 98% detection accuracy. With respect to the false-alarm probability, SIRA yields below 6% error. Moreover, \( I_U \) prediction error is only around 200 symbols which is much smaller than the maximum number of symbols, i.e., 2500.

Fig. 3(a) shows the average SFER performance under mobile traces where the fixed MCS 7 achieves the best performance, when disabling A-MPDU, due to the short range between transmitter and receiver during the collection of the traces. The baseline 802.11 suffers from the caudal losses, even if the channel condition is good in terms of RSS. This is similar to the tendency shown in Fig. 1(a). However, SIRA significantly mitigates the SFER explosion, roughly by 20% on average.

Fig. 3(b) depicts the throughput performance of standalone SGRA and SIRA interplaying with SGRA in various traces including static. If standalone SGRA is used, the throughput seriously decreases along with the increase of the degree of user mobility, as explained in Section II. However, the joint use of intra/inter-RCAs, i.e., SIRA+SGRA, remarkably alleviates the throughput degradation, and also shows higher throughput performance than standalone SGRA for all traces. Especially, when a station moves at an approximate constant speed of 1 m/s, SIRA achieves the maximum 56% throughput gain. Furthermore, SIRA shows slightly better throughput in static trace, not only because the wireless channel changes even if stations hold their position, but also because SIRA requires no extra overhead.

V. CONCLUSION AND FUTURE WORK

In this paper, the issue of unreliable transmission in A-MPDU of IEEE 802.11 is addressed, especially for the rapid dispersive fading channels. To resolve the issue, we have developed SIRA, a method for selecting the appropriate PHY rates on intra-frame basis by using PHY information without any protocol overhead. Our results show that the proposed scheme is effective and yields significant performance gain for all traces including static. To our best knowledge, in WiFi networks, this is the first rate control algorithm to address the issue of quickly adapting time-variant wireless channel during one-frame duration. As future work, we plan to extend SIRA by considering spatial multiplexing features.

REFERENCES