Performance Analysis of Channel-Dependent Rate Adaptation for OFDMA transmission in IEEE 802.11ax WLANs

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Abstract—**This paper investigates the application of the Received Bit Information Rate (RBIR) mapping technique to abstract the physical (PHY) layer in performing rate adaptation for IEEE WLAN 802.11ax systems. We observe that the modulation and coding scheme (MCS) obtained by PHY Layer Abstraction (PLA) is too conservative when used in practice. Motivated by this observation, we propose Hybrid Channel-Dependent Rate Adaptation (HCDRA) to map the measured SNR to an MCS value that maximizes the throughput while keeping the average Packet Error Rate (PER) below a threshold value. We evaluate HCDRA for a user on a Resource Unit (RU) in the OFDMA mode of transmission.**

The proposal of channel-dependent rate adaptation in OFDMA mode of transmission for IEEE WLAN 802.11ax is novel to the best of our knowledge. We implement and evaluate HCDRA in the standard-compliant MATLAB WLAN Toolbox and compare its performance with other well-known rate adaptation algorithms such as Automatic Rate Fallback (ARF), Adaptive ARF (AARF), Minstrel, and MutFed. More realistic situations with PHY impairments such as carrier frequency offset (CFO) and symbol timing offset are considered in all our simulations. Results show that HCDRA has better throughput performance compared to the four other algorithms we have evaluated. HCDRA is eminently implementable without any modification in the standard frames, and hence it is suitable for practical deployment.

Keywords—channel-dependent rate adaptation, OFDMA, PLA, RBIR, 802.11ax, SNR, WLAN Toolbox

I. INTRODUCTION

Wireless communication suffers from many time-varying phenomena such as signal attenuation, channel fading due to multipath propagation, and interference caused by other transmissions at overlapping frequencies. The time-varying nature of the wireless link limits its performance. This leads to packet loss or bit errors whenever the link quality is poor. To efficiently utilize the channel in such severe conditions, the sender must select the optimum transmission rate that the current channel condition can support and dynamically adapt the rate to the continuously varying channel. This is called rate adaptation. The efficiency of the rate adaptation algorithm (RAA) in selecting the optimal data rate for the current channel conditions directly impacts the throughput of the wireless system. Based on the method of estimation of channel conditions, the RAA can be broadly classified into two categories: (i) Implicit feedback, in which the transmitting station estimates the channel condition through the transmission history (success/failures) of the previous frame transmissions. (ii) Explicit feedback, in which channel quality is estimated based on the received signal strength at the receiver, and feedback is provided to the transmitter.

All the proposed rate-adaptation schemes use either or both the above methods to estimate channel conditions to perform rate adaptation [1, 2]. The standard does not provide any specification for a rate-adaptation scheme. However, the rate adaptation strategy must allow transmissions at rates that can be successfully decoded at the receiver [3].

Implicit feedback is a transmitter-driven rate adaptation scheme, and it is usually based on Packet Error Rate (PER). The main idea is that the sender selects an appropriate data rate based on the PER observed locally. This requires acknowledgment (ACK) frames to enable the sender to calculate the PER. Many frame-level rate adaptation schemes are proposed in the literature. Most popular algorithms falling under this category include Auto Rate Fallback (ARF), Adaptive ARF (AARF), and Minstrel [4-6]. Frame-level protocols, by design, are less responsive to channel variations as they require multiple frame receptions to estimate channel state at any data rate.

System performance can be significantly improved if the RAA captures the current channel condition more precisely. Explicit feedback is a receiver-driven rate adaptation scheme. The receiver takes a decision based on its estimation of the channel conditions and conveys its decision to the transmitter via different approaches using control frames such as Acknowledgments (ACK) [2]. These present some limitations, such as modifying the ACK frame that violates the standard.

The most cited works on Explicit feedback algorithms are presented in [7,8,9]. For fast-varying channels, SoftRate is proposed in [7]. [8] proposes a novel rate-adaptation scheme,

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MutFed, where the decision of rate selection relies on the mutual feedback of a transmitter and receiver pair. The authors in [9] have conducted a systematic measurement-based study to confirm that, in general, SNR is a good prediction tool for channel quality.

High Efficiency (HE) 802.11ax standard includes the HE sounding protocol to determine channel state information. It provides an explicit feedback mechanism where the STA sends back a transformed estimate of the channel state. HE Channel Quality Indicator (CQI) report field carries an array of received per-RU average SNRs for each space-time stream. Each per-RU average SNR is the arithmetic mean of the SNR in decibels over a 26-tone RU for which the feedback is requested [3]. Therefore, to use the advantages of SNR to estimate the channel quality, *the objective is to design a rate adaptation technique without any modification in the standard frames so that it is suitable for practical deployment.*

We propose a *Hybrid* rate adaptation strategy, as it *combines* the MAC layer information available at the transmitter based on the transmission history and the PHY layer information from feedback provided by the receiver to assess the channel conditions more accurately and choose the appropriate transmission rate. This achieves two-fold benefits of minimizing the number of retransmissions and thereby improving the application-level throughput. The primary contributions of this paper are (i) the design of a rate adaptation strategy, Hybrid Channel-Dependent Rate Adaptation (HCDRA), to choose the MCS more cleverly to maximize the throughput while keeping the average PER below a threshold value. (ii) implementation and evaluation of HCDRA using standards-compliant MATLAB WLAN Toolbox, generating 802.11ax PHY layer waveforms, passing through Indoor TGax channel model [3,14] with LDPC channel coding and OFDMA receiver processing.

This paper is organized as follows. Section 2 presents the proposed RAA in the literature and its shortcomings. Section 3 describes the PLA for 802.11ax downlink using the RBIR mapping technique and its validation using performance curves of an AWGN channel. Section 4 presents the HCDRA algorithm that uses delayed CSI feedback to improve the application-level throughput. Section 5 includes the implementation details, OFDMA receiver signal processing, and performance comparison of the proposed HCDRA algorithm with other RAA proposed in the literature. Finally, the summary of our work is presented in Section 6.

II. Related Work And Our Contribution

Implicit feedback generally uses frame-level protocols that require tens or hundreds of frames to estimate the channel condition accurately. ARF is the most widely implemented rate-adaption scheme. However, in stable channel conditions or fast channel variations, it does not perform well [4]. The authors in [5] have proposed AARF, in which the success threshold is continuously adapted, to better reflect the channel conditions by using Binary Exponential Backoff (BEB). The performance of the Minstrel algorithm that is based on the multi-rate retry chain concept is evaluated in [6]. Minstrel is widely implemented in popular wireless drivers such as *MadWiFi*, *Ath5k,* and *Ath9k*. The results in [6] show that while Minstrel performs well in many cases (particularly with "good" or "stable" channel conditions), the algorithm has difficulty achieving optimal throughput performance with "poor" or highly "dynamic" channel conditions.

SoftRate is presented in [7], a wireless bit rate adaptation protocol that computes the interference-free BER estimate using per-bit confidences called SoftPHY hints exported by the PHY layer. This protocol is proposed for fast-varying channels (due to high mobility) that can react to channel variations within a single packet-time. However, in indoor applications with pedestrian speeds, WLAN is a slowly varying channel. Hence, rate adaptation protocol need not observe the signal to this extent of timescale. The authors state that the SoftRate protocol incurs extra overhead in including a BER measurement in the link-layer ACK to respond to rapid channel variations.

In MutFed [8], the receiver calculates the average value of SNR after every tenth frame reception. This average SNR is used to select an appropriate transmission rate based on table look-up. The receiver then informs the transmitter about the selected transmission rate by sending the 10th ACK frame at the chosen transmission rate. MutFed has two issues for practical implementation. First, it requires a fair amount of computation by the STA to select an optimal rate. Second, the way of letting the transmitter know the chosen rate is not 802.11 standards-compliant, hindering its practical deployment.

We propose a channel-dependent rate adaptation algorithm that uses the RBIR PHY layer abstraction scheme [12, 14] to select an MCS value initially. Instantaneous CSI to select the MCS for every transmitted packet introduces unnecessary computational and protocol overhead for a slowly varying WLAN channel. *Delayed CSI feedback* is proposed, wherein the channel is estimated at the receiver using the Long Training Fields (L-LTF and HE-LTF) of packet preamble after every ten packets. In our algorithm, the Access Point (AP) performs the necessary computation and decides the optimal rate based on the SNR feedback in the HE CQI report of the STA. RBIR PLA is used initially to predict the PER for all possible MCS, based on the measured SNR. Our algorithm then maps the measured SNR to an optimum MCS value that maximizes the throughput while keeping the average PER below a threshold value.

The proposal of hybrid rate adaptation that *combines* the MAC information available at the transmitter and the PHY layer feedback information of the receiver in OFDMA mode of transmission in IEEE 802.11ax is novel to the best of our knowledge. Other novel features in the implementation of our algorithm that make it much closer to real-time packet processing are as follows:

(i) In receiver processing, while recovering the 802.11ax packet, we do realistic Least squares (LS) channel estimation and perform time and frequency synchronization over frequency-selective TGax channel models instead of the oversimplified ideal channel estimation and synchronization assumptions. This is one of the unique aspects of our work compared to open TGax technical reports and previous works [12,17], wherein perfect CSI and synchronization are assumed.

(ii) The L-LTF and HE-LTF fields of the packet preamble are used to estimate the channel, and these channel estimates are used to equalize and decode the pre-HE-LTF field and HE modulated field, respectively.

(iii) More realistic situation with the PHY impairments such as carrier frequency offset (CFO), symbol timing offset is considered. In front-end processing of the receiver, initially, the packet is detected. It is followed by coarse CFO correction, timing synchronization, and fine CFO correction. This is another vital aspect of our work, which captures the true-SNR required in mapping it to a particular MCS value. We have found that none of the earlier works considered these PHY impairments while evaluating their RAA. The HCDRA is evaluated for a single user (SU) on a fixed RU, considering an RU size of 26 tones. Its performance is compared with ARF and other algorithms.

Most of the existing RAA are implemented and evaluated using the NS-3 simulator, which does not model any potential frequency-selective fading effects [10]. We have designed and evaluated HCDRA and other existing algorithms using a reliable link simulator, MATLAB WLAN Toolbox of MathWorks, to model end-to-end link-level SISO transmit-receive link with IEEE standard defined channel models [3, 14]. A recent transaction paper [11] for 802.11ax fast simulations in complex systems environments uses MATLAB WLAN Toolbox, as it is more credible and 802.11 standard-compliant.

III. PHY Layer Abstraction using RBIR Mapping

PHY layer abstraction (PLA) helps predict a link's performance in a computationally efficient way. In OFDM/Multicarrier communication systems, the PER performance varies as a function of sub-carrier SNRs. Thus sub-carrier SNRs serve as the basis for PER prediction. The underlying principle is to map the sequence of sub-carrier SNRs to a single effective SNR (SNR_{eff}). This quantity then acts as a link between AWGN channel PER and multipath frequency selective channel PER for a given coding scheme (BCC or LDPC), packet size, and MCS value.

The most popular PLA methods are Effective Exponential SNR Mapping (EESM), and Information Theory-based Received Bit Information Rate (RBIR) mapping [15-18]. In [16], EESM is chosen as the PLA technique for 802.11n and LTE downlink, and it is stated that EESM has high hardware implementation complexity. The highly cited Brueninghaus et al. [18] used EESM and RBIR based PLA to evaluate the MIMO-OFDM system. They showed that the mutual information-based PLA has an excellent PER prediction accuracy under all tested conditions, and it is well suited for modeling the link performance of MIMO-OFDM systems.

A. RBIR Mapping Technique

We have implemented RBIR based PLA, which uses a vector of per-subcarrier SNRs, SNR_i, to calculate an effective average SNR, SNR_{eff}. This effective SNR can be used to determine the performance of a frequency selective fading channel using link-level simulation results of an AWGN channel. For each MCS, the mapping function is optimized so that the PER under the AWGN channel for $SNR = SNR_{eff}$ approximates the PER of any frequency selective channel characterized by sub-carrier SNRs, SNR_i.

For a SISO system, post-processing SNR for i^{th} sub-carrier is obtained from the channel and noise estimates [17] as

$$SNR_i = \frac{P_{tx}}{N\sigma_i^2}|H_i|^2 \tag{1}$$

where $\sigma_i^2 = B_{sc}KT$ with $B_{sc} = 78.125$ KHz, sub-channel bandwidth in 802.11ax and N is the total number of pilot and data sub-carriers (=242 for 20MHz channel in 802.11ax). The effective SNR is calculated [14] as

$$SNR_{eff} = \alpha \cdot \phi^{-1}\left(\frac{1}{N_d}\sum_{i=1}^{N_d}\phi\left(\frac{SNR_i}{\beta}\right)\right) \tag{2}$$

where N_d is the number of data subcarriers, ϕ^{-1} is the inverse mapping function, α and β are tuning parameters. The mapping function ϕ for RBIR technique, assuming coded M-QAM modulation [14], is defined by

$$\phi(SNR, M) = log_2 M - \frac{1}{M}\sum_{m=1}^{M} E_U\left\{log_2\left(\sum_{k=1}^{M} exp\left[\left(|U|^2 - \left|\sqrt{SNR}(s_k - s_m) + U\right|^2\right)\right]\right)\right\} \tag{3}$$

where U is a zero-mean complex Gaussian random variable with unit variance, M is the number of constellation points, s_k is a constellation point with normalized energy. The Methodology for RBIR PHY layer Abstraction is shown in Fig.1.

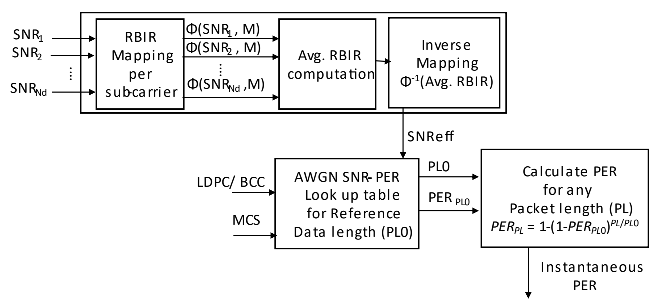

Fig. 1. Block diagram of RBIR PHY Layer Abstraction

We consider a single user occupying 20MHz bandwidth at a carrier frequency of 5.25GHz, a SISO Model-D channel with LDPC coding to implement the RBIR. The frequency response is estimated on all subcarriers over 20MHz. From the channel and noise estimates, sub-carrier SNRs, $SNR_1, SNR_2, \ldots\ SNR_{N_d}$ are calculated. The RBIR (information bits) per sub-carrier is obtained by mapping the SNR per sub-carrier. Then the average RBIR is computed. The effective SNR, SNR_{eff}, is obtained by inverse mapping the average RBIR.

B. PER Estimation using RBIR mapping technique

The PER vs. SNR look-up table of an AWGN channel for each MCS is generated with the granularity of 0.25dB. Since it is not feasible to generate such look-up tables for all packet lengths, TGax evaluation methodology [14] recommends estimating the PER for any desired packet length by linearly interpolating the appropriate AWGN link-level curve of the reference packet length (PL_0). The PER for any packet length (PL) [14, 17] is obtained by

$$PER_{PL} = 1 - \left(1 - PER_{PL_0}\right)^{PL/PL_0} \tag{4}$$

where PER_{PL_0} is the PER at the reference packet length.

C. Verification and Validation of RBIR using Link-level simulation and AWGN curves

RBIR is highly accurate and less dependent on optimization of fitting parameters than EESM [18]. The tuning parameters α and β are set to 1 to further simplify processing with a minor impact on PER prediction accuracy [12].

The PER from a link-level simulation at each SNR point is compared with the PER estimates obtained using the RBIR based PLA to verify the PHY layer abstraction, as shown in Fig. 2. At each SNR point (see Fig. 2), at most 10^5 packets or 10^3 erroneous packets were simulated for MCS 0 to 9. For each MCS, the estimated PER follows the link-level simulation curve, implying successful PHY abstraction.

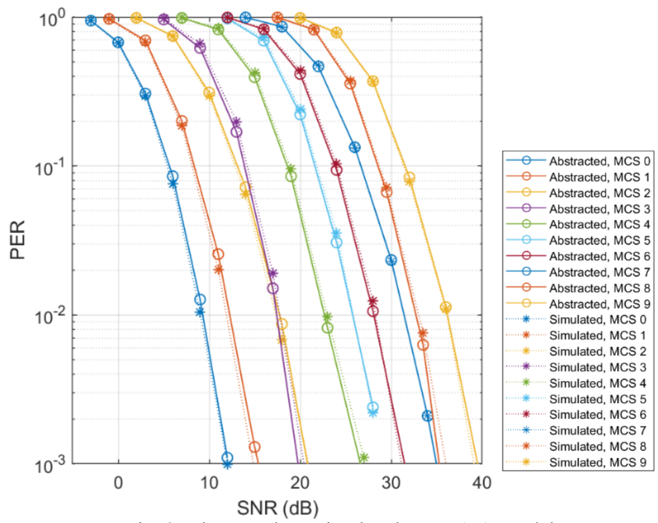

Fig. 2. Abstracted vs. Simulated PHY, 1x1, model-D

IV. Channel-Dependent Rate Adaptation

A. Motivation

Rate adaptation algorithms minimize the risk of packet loss by using a lower data rate than the channel permits since packet loss is expensive. Therefore for every successful transmission, there is some *link margin*. It is the difference between the instantaneous channel SNR (actual) and the minimum SNR (dependent on MCS) required for the successful decoding of the packet. The value of the link margin depends on various parameters such as the accuracy of SNR measurement, the permissible MCS, and how conservative the rate adaptation algorithm is [19].

The IEEE 802.11 wireless standard supports multiple discrete data rates at the PHY layer. The device may transmit at a rate higher than the base rate if channel conditions so permit. This is because there could be considerable slack between the data rate suggested by RAA and the data rate the channel could actually support. This is the motivating feature that has been adopted in our proposed algorithm for choosing the MCS value wisely depending on the current channel condition to maximize the throughput while maintaining the PER below the threshold.

The coherence time of the channel is approximately the duration of time over which multipath fading effects are expected to remain the same. Coherence times are a few tens of milliseconds long in a slow fading indoor WLAN channel, basically designed for static nodes or pedestrian speeds. Hence, fading happens at a timescale corresponding to multiple frame transmissions [20]. HCDRA is designed to use this fact to observe the varying signal over the timescale of multiple frames in the WLAN channel.

B. The HCDRA Algorithm

This section presents the HCDRA algorithm. Let the sequence of transmission of packets be divided into multiple windows, with each window having 'w' packets, as illustrated in Fig. 3.

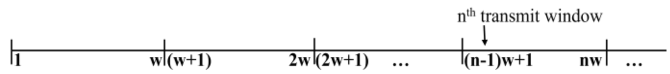

Fig. 3. Representation of transmission of packets into multiple windows

We propose a delayed CSI feedback, in which the channel is estimated at the receiver using the packet preamble at the end of each window, i.e., after every 'w' packets.
The workflow of the algorithm is as follows:

Step 1. Estimate average SNR of a resource unit (RU) from the channel and noise estimates of RU, at packet # w, 2w, 3w, etc.

Step 2. Use PHY layer abstraction [12, 14] to determine the PER for all MCS (MCS 0-9) at the estimated SNR of step 1.

Step 3. Select the highest MCS for which the estimated PER <= threshold PER. Let the MCS suggested by PLA be **'m'**.

Step 4. Error Rate is computed at the end of the n^{th} window, considering the packets '(n-1)w+1' to 'nw' ∀ n >1, based on the successful/failed reception of the ACK frame.

Step 5. If (computed Error Rate)$_n$ in step 4 <=0.1 **AND** if MCS suggested in step 3 <=5, choose MCS **'m+1'** for the $(n+1)^{th}$ window.

Step 5a. The MCS suggested in step 5 is used for all 'w' packets in $(n+1)^{th}$ window, unless either of two specific conditions occurs: (i) the transmission of packet #(nw+1) is not successful, or (ii) there are two consecutive packet errors any time during $(n+1)^{th}$ transmission window. In either case, MCS is decreased by 1, so that it becomes **'m'**.

At any SNR, the BER is a monotonically increasing function of the bit rate. Hence, an increase in MCS by one level against the MCS obtained by PLA is not chosen at higher-order MCS (beyond 5) to control packet losses. Thus, the algorithm is carefully designed to make the best use of good channel conditions while keeping a hold on possible packet errors. This gives the benefit of achieving high throughput by reducing the number of retransmissions.

V. Performance Evaluation Using MATLAB WLAN Toolbox

The design, analysis, and performance evaluation of HCDRA are done using the standards-compliant, credible link simulator MATLAB WLAN Toolbox of MathWorks.

A. Simulation settings

Table I summarizes the simulation parameters considered to evaluate the proposed and existing rate adaptation algorithms.

TABLE I. SIMULATION PARAMETERS

General parameters	
Distance (d)	5m
Interference power(P_i)	0W
Transmit power per packet (P_{tx})	1W
Payload length (P_b)	500 bytes
Signal Flow	Downlink
Threshold PER	0.1
Channel parameters	
Channel Bandwidth	20MHz
Carrier Frequency	5.25GHz
Delay profile	TGax Channel Model-D
Speed of scatterers/ users	0.089km/hr
Channel coding	LDPC
Specific for IEEE 802.11ax	
Mode of transmission	OFDMA
Number of RUs	9
RU size / OFDMA sub-carriers per user	26

We now illustrate steps 2 and 3 of HCDRA of section 4B. The average SNR of RU1 (26tones) is estimated at the receiver using the HE-LTF field of packet preamble. The average SNR of RU1 for the 1000th packet is 22.57dB. The PER is estimated for all possible MCS by interpolating the SNR-PER RBIR look-up-table (refer to Fig. 2) by setting the query point as 22.57dB. This is done to find the maximum MCS the RU can support, so the PER is less than the threshold PER (0.1). Fig. 4 shows the PER estimation for all possible MCS based on the average SNR of RU1. The PER monotonically increases with the MCS index, as higher MCS requires higher SNR. MCS 6 is the highest MCS that meets the PER requirement.

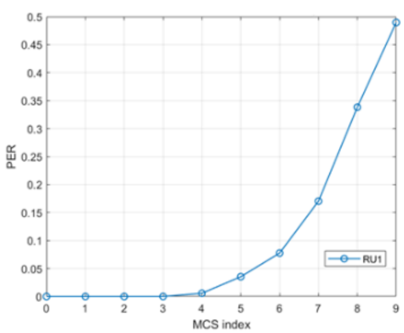

Fig. 4. Estimated PER for a user on RU1 for MCS 0-9

B. OFDMA- Receiver Signal Processing

This is the procedure implemented in MATLAB at the receiver. Front-end processing begins with packet detection. The steps that follow are:

- Coarse frequency offset estimation and correction using L-STF and symbol timing synchronization using L-SIG.
- Fine frequency offset and correction are done using L-LTF.
- L-LTF is demodulated to perform channel estimation. The L-LTF channel estimates are used to equalize and decode pre-HE-LTF fields.
- HE-SIG-A is decoded to obtain common transmit configuration of all users such as Guard interval, HE-LTF type, downlink/ uplink indicator, etc.
- HE-SIG-B is decoded, and user-specific properties, such as RU allocation information, are inferred from its user field.
- HE-LTF field is demodulated, followed by channel estimation. HE-LTF channel estimates are used to equalize and recover PSDU bits for each user in the HE-Data field.

C. Behavior of HCDRA over the time-varying channel

We evaluate HCDRA for a user on RU1 in the OFDMA mode of transmission. WLAN is a slow-fading channel; the sender's signal fades sharply once every 10-100 milliseconds, typically resulting in a burst of packet losses at higher bit rates. In response, HCDRA lowers the bit rate quickly; it also adapts "upwards" quickly when the channel conditions improve. Fig. 5(i) shows the MCS used for the transmission of each packet, and it is dependent on the estimated SNR of Fig. 5(ii). The bit error rate (BER) per packet in Fig. 5(iii) depends on the channel conditions, SNR, and MCS used. The throughput is calculated for a sliding window of 10 packets. Each point in Fig. 5(iv) represents the number of successfully recovered data bits over the last ten packets. The throughput decreases whenever MCS decreases or a packet error occurs.

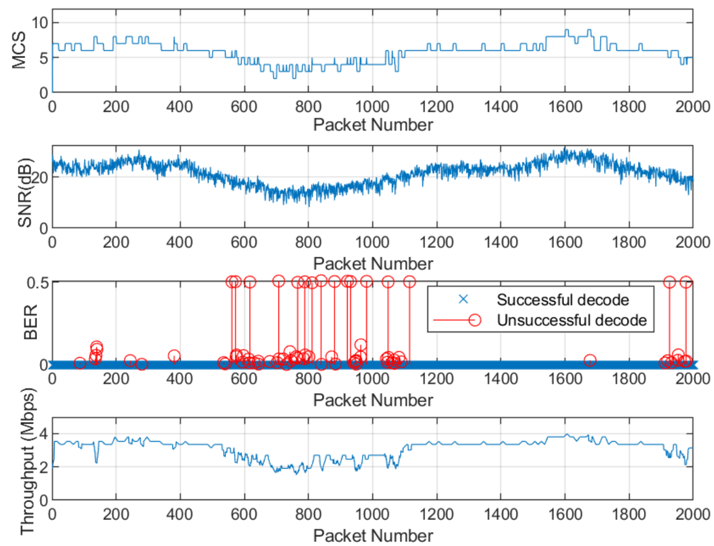

Fig. 5. (i) MCS selected for transmission (ii) Estimated SNR (iii) Instantaneous BER per packet (iv) Throughput over last ten packets

D. Comparison Results of HCDRA with other RAA

We evaluate and compare the performance of HCDRA with four other algorithms, namely ARF, AARF, Minstrel, and MutFed, using the MATLAB WLAN Toolbox. Every algorithm is evaluated for 12 simulation runs; each run defines a new channel realization. The number of packets being processed in every run is 2000, with a payload size of 500 bytes. Each packet passes through the i.i.d TGax channel. Fig. 6a shows the throughput and PER performance of all five algorithms at 12 different channel realizations. For each point plotted, throughput is the aggregate number of bits in the payloads of all successfully received packets, divided by the time needed to transmit all 2000 packets. Channel realizations 6 and 7 capture the SNR degradation due to poor channel conditions.

HCDRA assumes that the AP learns the downlink SNR periodically using the HE-CQI Report field. HCDRA outperforms the four other algorithms for all channel conditions. ARF has the worst PER performance as it inherently tries to increase the data rate after every ten successful transmissions (success threshold) without having the knowledge of channel conditions. Though MutFed has the best PER performance, it is more conservative in MCS selection, and hence the transmission time of MutFed is larger compared to ARF, AARF, and HCDRA. Minstrel also has poor PER as random rates are used during 10% of the transmission time. Any transmission window uses one of the four possible rates based on the retry-chain concept. Most of the time, the transmission rates would be lower even when the channel conditions are good, increasing the packet transmission time (see Fig. 6b). Therefore, Minstrel has the largest transmission time of all algorithms and has poor throughput performance.

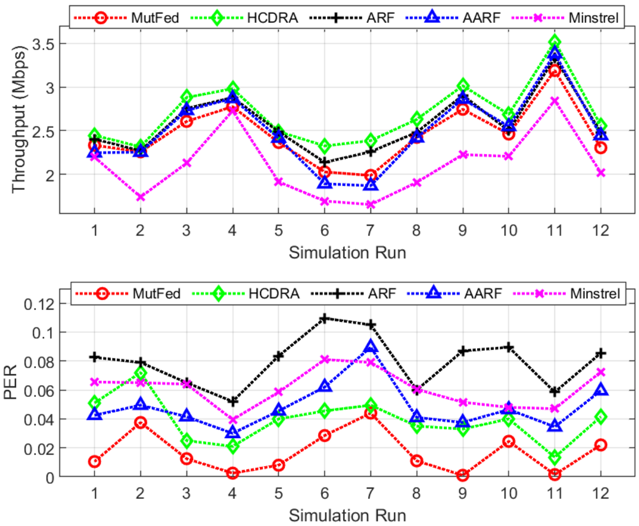

Fig. 6a. (i)Throughput and (ii) PER performance for different channel realization of 26 tones RU

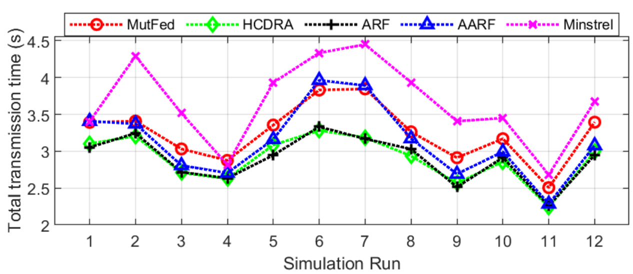

Fig. 6b. Total transmission time for transmission of 2000 packets in each channel realization of 26 tones RU

VI. Conclusion

In this paper, we made three key contributions. First, we identified and confirmed that the MCS obtained using RBIR PHY Layer Abstraction is too conservative and highlighted numerous factors that significantly affect the rate-adaptation schemes. Second, we designed and evaluated a novel Hybrid Channel-Dependent Rate Adaptation that can accurately determine channel conditions and adapt to varying channel conditions more quickly than the existing solutions. Third, more realistic PHY Layer impairment such as CFO is estimated and corrected, together with channel estimation, time, and frequency synchronization in evaluating all five algorithms.

Through MATLAB WLAN Toolbox simulations, the thorough evaluation showed that HCDRA achieves 7-28% throughput gain for an interference-free scenario compared to existing work. HCDRA is eminently implementable because the STA provides CQI feedback, using feedback mechanisms that are recommended by the standard. Therefore, there is no need for any specially customized mechanisms to implement our proposed algorithm.

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References

[1] Guanhua Wang, Shanfeng Zhang, Kaishun Wu, Qian Zhang, and Lionel M. Ni, "TiM: Fine-Grained Rate Adaptation in WLANs," IEEE IEEE Transactions on Mobile Computing, Vol. 15, No. 3, March 2016.

[2] I. Sammour and G.Chalhoub, "Evaluation of Rate Adaptation Algorithms in IEEE 802.11 Networks," *Electronics* 2020, No. *9*, 1436, Sept 2020.

[3] "IEEE P802.11ax™/D4.1 Draft Standard for Information technology—Telecommunications and information exchange between systems Local and metropolitan area networks— Specific requirements- Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," IEEE P802.11ax™/D4.1, April 2019.

[4] A. Kameman and L. Montban, "WaveLAN II: A high-performance wireless LAN for the unlicensed band," Bell Labs Technical Journal, pages 118-133, 1997.

[5] M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: a practical approach," Proceedings of the 7th ACM international symposium on Modelling, analysis, and simulation of wireless and mobile systems, pages 126-134, 2004.

[6] Dong Xia, Jonathan Hart, Qiang Fu, "On the Performance of Rate Control Algorithm *Minstrel*," IEEE 23rd International Symposium on Personal, Indoor, and Mobile Radio Communications - (PIMRC), 2012.

[7] M. Vutukuru, H. Balakrishnan, and K. Jamieson, "Cross-layer wireless bit rate adaptation," ACM SIGCOMM 2009, Vol. 39, Issue 4, 2009.

[8] S. Khan, S. A. Mahmud, H. Noureddine, H. S. Al-Raweshidy, "Rate-adaptation for multi-rate IEEE 802.11 WLANs using mutual feedback between transmitter and receiver," IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications, 2010.

[9] J. Zhang, K. Tan, J. Zhao, H. Wu, and Y. Zhang, "A practical SNR guided rate adaptation," IEEE International Conference on Computer Communications (INFOCOM), Phoenix, AZ, USA, 2018.

[10] "Design documentation of ns-3 Network simulator," https://www.nsnam.org/docs/models/html/wifi-design.html

[11] Sian Jin, Sumit Roy, T. R. Henderson, "Efficient PHY Layer Abstraction for Fast Simulations in Complex System Environments**,"** IEEE Transactions on Communications, Vol. 69, No. 8, Aug. 2021.

[12] Pengfei Xia, Ron Murias, IEEE 802.11-14/0527-r1, "PHY Layer Abstractions for TGax System Level Simulations," May 2014.

[13] Evgeny Khorov, Anton Kiryanov, Andrey Lyakhov and Giuseppe Bianchi, "A Tutorial on IEEE 802.11ax High-Efficiency WLANs," IEEE Communication Surveys and Tutorials, Vol. 21, Issue 1, 2019.

[14] R. Porat, Matt Fischer, IEEE 802.11-14/0571r12, "IEEE P802.11 Wireless LANs: 11ax Evaluation Methodology," Jan 2016.

[15] G. R. Al-Juboori, D. Halls, A. Doufexi, and A. R. Nix, "A link quality model for generalized frequency division multiplexing," IEEE 85th Vehicular Technology Conference (VTC Spring), IEEE, June 2017.

[16] J. Wu, Z. Yin, J. Zhang, and W. Heng, "Physical layer abstraction algorithms research for 802.11n and LTE Downlink," International Symposium on Signals, Systems and Electronics, Vol. 1, Sept 2010.

[17] R. Patidar, S. Roy, T. Henderson, and A. Chandramohan, "Link-to-System Mapping for ns-3 Wi-Fi OFDM Error Models," Workshop on ns-3, June 2017.

[18] K. Brueninghaus, D. Astely, T. Salzer, S. Visuri, A. Alexiou, S. Karger, and G. Seraji, "Link performance models for system-level simulations of broadband radio access systems," in IEEE 16th International Symposium on Personal, Indoor and Mobile Radio Communications. IEEE, 2005.

[19] A. Cidon, K. Nagaraj, S. Katti, and P. Viswanath, "Flashback: Decoupled lightweight wireless control," in Proc. ACM SIGCOMM, Vol. 42, Issue 4, Oct. 2012, pp. 223–234.

[20] Kakyung Jung, Ted Taekyoung Kwon, Kideok Cho, Yanghee Choi, "REACT: Rate Adaptation using Coherence Time in 802.11 WLANs," Computer Communications, Vol. 34, July 2011, Pages 1316-1327.