

Improving Throughput by Integrated Power Allocation and Rate Selection in IEEE 802.11ac Downlink Multi-User MIMO

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Abstract—In order to cope with the ever-increasing demand for high throughput WLANs, IEEE 802.11ac standard will support a wide range of new features, including downlink multi-user MIMO and higher order modulation in its physical layer. This paper addresses the design of the rate selection and transmission power allocation in downlink multi-user mode of this standard. The suggested integrated scheme utilizes the channel state information to determine the most appropriate transmission power and rate of each downlink stream so that the air time utilization in each multi-user transmission is maximized, and accordingly the throughput is improved. The simulation results generated by the IEEE 802.11ac channel and physical layer models show a significant gain with the suggested scheme in terms of the goodput achieved in the MAC layer.

Index Terms—IEEE 802.11ac, DL-MU-MIMO, rate selection, power allocation.

I. INTRODUCTION

The last decade has witnessed the proliferation of wireless LAN (WLAN) into the new applications, such as HD video streaming/distribution and rapid upload/download of data. These new applications are driving increasing demand for high throughput communication. Therefore, to cope with this demand, a new amendment, 802.11ac, has been under development by the IEEE 802.11 working group. The goal of 802.11ac is to support wireless distribution of multiple multimedia/data streams with data rates of 500 to 1000 Mbps in the 5 GHz band. Some key features for increasing data throughput are wider channel bandwidths up to 160 MHz, higher-order 256 QAM modulation and support for multiple (up to 8) spatial streams using multiple-input multiple-output (MIMO) techniques. However, the most major PHY layer improvement of IEEE 802.11ac compared to its predecessor standard is its downlink multiuser MIMO (DL-MU-MIMO) transmission support. In the DL-MU-MIMO transmission, an access point (AP) can take advantage of the spatial multiplexing gain to transmit data streams of multiple stations (STAs) at the same time, and accordingly, it can achieve significant channel utilization and MAC layer throughput. In DL-MU-MIMO, AP adopts beamforming technique to steer signal maxima over the desired STAs while minimizing the interference caused at other STAs. In order to perform beamforming, the AP needs to know the channel state information (CSI) of each intended STA. The rate selection is a promising technique for providing increased throughput and performance guarantees under

specified Quality of Service (QoS) requirements. It adjusts the modulation and coding scheme (MCS) of a transmission dynamically according to the channel variation. A wide range of approaches have been proposed for rate selection in current the WLAN standards. However, rate selection problem in 802.11ac DL-MU-MIMO is different in two aspects from that problem studied in the context of the current standards. First, the major assumption of the rate selection algorithms suggested in the literature is that the CSI is not available at the transmitter. However, the availability of the CSI at the AP for DL-MU-MIMO operation provides the opportunity to utilize this already available information for the rate selection. Second, in DL-MU-MIMO transmission, the frames of multiple downlink STAs constitute a PHY protocol data unit (PPDU) and are transmitted simultaneously. The transmission time of this PPDU is determined by the slowest downlink stream; therefore, assigning same transmission power to all downlink streams and choosing highest feasible transmission rate for each stream does not necessarily achieves the maximum throughput. Indeed, the parallel transmission capability provided by DL-MU-MIMO can be under-utilized when transmission times of the data streams of the intended STAs are different. Therefore, in order to maximize the transmission parallelization and, accordingly, the channel utilization, we need to adjust transmission rate according to data size of each downlink STA. In this paper, we put forward a practical integrated approach to the transmission power allocation and rate selection in DL-MU-MIMO. The proposed approach takes into account current channel state and total transmission power constraint to determine transmission parameters of each down-link data stream. It chooses modulation, coding and transmission power of each stream such that the throughput achieved by the DL-MU-MIMO transmission is maximized and the QoS requirement of each intended STA is satisfied.

II. RELATED WORK

A technique for frame aggregation in IEEE 802.11ac is proposed in [1] with the goal of maximizing the parallelization capability of MU transmission. This technique considers a single transmission rate, consequently by aggregating same number of frames into downlink streams the payload of them has the same duration which allows maximizing parallel transmission. Jeon et al.[2] present a channelization scheme

which enables an increased transmission parallelization. Their scheme adaptively determines the channel width of each downlink stream according to its payload size and transmission rate such that all downlink streams of a MU transmission have almost the same duration. Neither of these works discuss how transmission rate is determined. Particularly in the scheme of Jeon et al. the channel sounding is performed after determination of channel width, therefore the transmission rate using which channelization has been performed may not be appropriate choice according to the current channel state.

Rate adaptation in WLAN has received a significant attention in the context of the previous 802.11 standards. The rate adaptation algorithms can be classified into two main categories: statistic based and CSI based algorithms. In the statistics-based algorithms channel estimation and accordingly rate selection is performed by sender through maintaining statistics about previous transmissions such as received ACKs, retry count and achieved throughput [3]. These algorithms usually use a probing mechanism to update the required statistics which makes it to converge slowly to a desirable rate. The available channel state knowledge (usually at receiver) is used to select the transmission rate by the CSI based algorithms [4]. In these algorithms, CSI along with other parameters that impact FER like MCS and frame length are mapped to a Link Quality Metric (LQM), by which the desirable rate is selected.

III. SYSTEM MODEL

We consider an infrastructure BSS in which an AP equipped with M antennas communicates with N single antenna STAs. Using various MCSs the AP supports a set of transmission rates, $R = \{r_{min}, r_{min+1}, \dots, r_{max-1}, r_{max}\}$. For a specific amount of transmission power constraint and channel state, different transmission rates achieve to the different frame error rates (FER). We assume a frequency selective wideband channel at downlink that is divided into L narrowband frequency flat subcarriers. The MIMO channel matrix affecting subcarrier l , $1 \leq l \leq L$, can be expressed as $\mathbf{H}_l = [\mathbf{h}_{l_1}^T, \mathbf{h}_{l_2}^T, \dots, \mathbf{h}_{l_N}^T]^T$ where $[\cdot]^T$ is the matrix transpose, and $\mathbf{h}_{l_k} = (h_{l_{k1}}, h_{l_{k2}}, \dots, h_{l_{kM}})$ the coefficients of the downlink channel from M antennas of the AP to the single antenna of the k th STA. IEEE 802.11ac includes channel sounding mechanisms by which the AP can obtain these coefficients.

The AP supports DL-MU transmission mode by which it can simultaneously transmit to $K \leq M$ STAs. DL-MU has been implemented using MIMO beam forming (BF). In BF, the STAs streams are separated by different beam forming weights. Let $\mathbf{w}_{l_k} = (w_{l_{k1}}, w_{l_{k2}}, \dots, w_{l_{kN}})$ and p_{l_k} be, respectively, the beam forming vector and the transmission power for k th STA on subcarrier l . For the signal received by k th STA on subcarrier l we have the following:

$$y_{l_k} = \sqrt{p_{l_k}} \mathbf{h}_{l_k} \mathbf{w}_{l_k} s_{l_k} + \sum_{j \neq k} \sqrt{p_{l_j}} \mathbf{h}_{l_j} \mathbf{w}_{l_j} s_{l_j} + n_k \quad (1)$$

where $\mathbf{s}_l = (s_{l_1}, s_{l_2}, \dots, s_{l_N})^T$ demonstrates the transmitted symbols in that subcarrier from the M transmit antennas of the AP, and n_k is additive white Gaussian noise (AWGN) with variance of σ_k^2 observed at the k th STA.

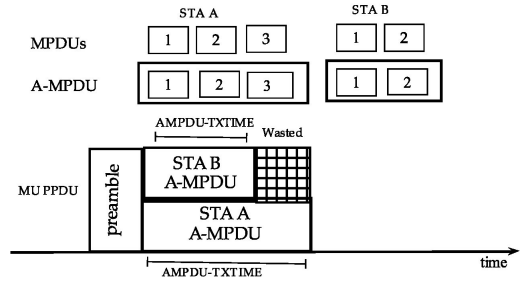


Figure. 1. Downlink multi-user PPDU transmission toward two stations with different amount of frames in each stream.

We assume zero forcing beam forming (ZFBF) [5] has been adopted by the AP. In ZFBF, beamforming vectors are selected such that they satisfy the zero-interference condition $\mathbf{h}_{l_k} \mathbf{w}_{l_j} = 0$ for $j \neq k$. Let C , $|C| = K$ be a subset of STAs to which the AP intends to transmit and $\mathbf{H}_l(C)$ is the corresponding submatrices of $\mathbf{H}_l$. Then $\mathbf{w}_{l_k}$ is obtained by normalizing the k th column of $\mathbf{W}_l(C)$, which is defined as

$$\mathbf{W}_l(C) = \mathbf{H}_l(C)^* (\mathbf{H}_l(C) \mathbf{H}_l(C)^*)^{-1} \quad (2)$$

where $[\cdot]^*$ denotes the conjugate transpose of a matrix.

The effective channel gain [6] of downlink channel toward k th STA in subcarrier l can be expressed as

$$g_{l_k} = \frac{1}{\|\mathbf{h}_{l_k} \mathbf{w}_{l_k}\|^2} = \frac{1}{[(\mathbf{H}_l(C) \mathbf{H}_l(C)^*)^{-1}]_{k,k}} \quad (3)$$

where $[\cdot]_{ij}$ is the element of a matrix in the i th row and the j th column, and $\|\cdot\|$ is the norm of a vector. In DL-MU-MIMO communication the downlink channel of the k th STA is characterized by effective channel gain of its all subcarriers which we denote it by g_k , that is $g_k = \{g_{1_k}, \dots, g_{L_k}\}$.

The total amount of transmission power for DL-MU, P_T , is allocated across the downlink streams. Furthermore, all the subcarriers of a downlink channel have been allocated the same amount of power. We assume non-saturated traffic load for each downlink stream, namely, each station can have different amount of frames to be transmitted by AP. All active STAs share a single finite-buffer space, in which by active STA we mean a STA that has a frame in the AP. In each transmit opportunity (TXOP), a scheduling algorithm selects the STAs that should be served in this TXOP. The scheduling algorithm chooses the STAs based on the FIFO policy with respect to the their first waiting frame. Each STA has a quality of service (QoS) requirement in terms of the desired maximum FER. The AP is informed about the QoS requirement of all the STAs within the BSS, and adjusts the transmission power and MCS such that the QoS requirement of each STA is satisfied.

IV. THE PROPOSED SCHEME

In this section, we explain the proposed scheme by which the AP determines transmission parameters including MCS and power of each stream of a DL-MU-MIMO PPDU in each TXOP. In order to get insight about the motivation of designing this scheme, consider the Figure. 1 that illustrates the transmission of a PPDU in the IEEE 802.11ac MU mode. In IEEE 802.11ac the frames, or more precisely the MAC

protocol data units (MPDUs) of a particular STA can be aggregated into a single MAC layer data unit called A-MPDU which is transmitted in a single TXOP. The A-MPDU of each STA is modulated and encoded independently with its own MCS. As shown in Figure. 1 if the time required for transmitting the A-MPDU of each STA, which is called the AMPDU-TXTIME of that STA, is different from the others, part of the link capacity is wasted when they are transmitted simultaneously in a single DL-MU-MIMO PPDU. We can select the transmission parameters of A-MPDU of each STA based on the size of that A-MPDU such that the amount of the wasted channel time during the transmission of the PPDU is minimized, and accordingly the channel capacity utilization is improved. For this purpose, we choose transmission rate of each A-MPDU in such a way that the goodput of the PPDU transmission carrying that A-MPDU is maximized. The goodput here is defined as

$$GP = \frac{(\sum_{k=1}^K n_k) L_f}{T_{BO} + DIFS + T_{ACS} + T_{PHY} + T_{MUA} + \max_{k=1 \dots K} \{ \frac{(n_k L_f + L_o)}{r_k} \}} \quad (4)$$

where L_f is the frame size, and T_{BO} and T_{PHY} represent the average back off duration and transmission time of the PHY-layer headers, respectively. T_{MUA} denotes the time spent for the MU acknowledgment process which can be computed as $K \cdot (2SIFS + T_{BAR} + T_{BA})$, where T_{BAR} and T_{BA} are the transmission time of block ACK request frame and block ACK frame, respectively. L_o is the length of the aggregation and MAC layer overhead. Moreover, n_k and r_k shows the number of frames aggregated into the A-MPDU of the k th STA and transmission rate of those frames, respectively. T_{ACS} is the average time spent for channel sounding g , which can be estimated as

$$T_{ACS} = \frac{\text{Average transmission time of a DL-MU-MIMO PPDU}}{\text{Average sounding period}} T_{CS} \quad (5)$$

where T_{CS} is the time required for a channel sounding round. We set the average sounding interval to 10 ms as suggested by [7].

Given the number of frames aggregated into the A-MPDU of each scheduled STA, i.e. n_i s, the objective of the proposed scheme is to dynamically determine the transmission rate of each downlink stream and accordingly its transmission parameters, so that the goodput is maximized while each STAs FER requirement is guaranteed and total transmission power constraint is satisfied. The objective function can be formulated as follows:

$$\begin{aligned} & \arg \max_{r_k} GP \\ & \text{subject to} \\ & r_{min} \leq r_k \leq r_{max}, \\ & FER_k \leq FER_{target}, \\ & \sum_{k=1}^K p_k \leq P_T. \end{aligned} \quad (6)$$

where FER_{target} is the target FER of k th STA and p_k is the minimum required power to transmit its stream such that

Algorithm 1 Rate determination and power allocation

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1:  $p_{total} \leftarrow 0$ 
2: for  $i = \max$  downto  $\min$  do
3:    $r_K \leftarrow rate_i$ 
4:    $p_K \leftarrow f(r_K, FER_{target}, g_K)$ 
5:    $\varepsilon \leftarrow n_K / r_K$ 
6:    $p_{total} \leftarrow p_{total} + p_K$ 
7:   for  $j = K - 1$  to  $1$  do
8:      $r_{temp} \leftarrow n_j / \alpha$ 
9:      $r_j \leftarrow \text{find\_nearest\_rate}(r_{temp})$ 
10:     $p_j \leftarrow f(r_j, FER_{target}, g_j)$ 
11:     $p_{total} \leftarrow p_{total} + p_j$ 
12:   end for
13:   if  $p_{total} \leq P_T$  then
14:     return  $r_1, r_2, \dots, r_K$  and  $p_1, p_2, \dots, p_K$ 
15:   end if
16: end for

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the FER_{target} is guaranteed. p_k is a function of FER_{target} , r_k and g_k . That is, $p_k = f(FER_{target}, r_k, g_k)$ and $f(\cdot)$ is a nonlinear function based on the used modulation and coding. We discuss how to determine this function in the next section. In order to solve (3), we design a greedy algorithm, details of which are described in Algorithm 1. In this algorithm, without loss of generality, we assume $n_1 \leq n_2 \leq \dots \leq n_K$. At first step, we select the highest rate for the stream that has the largest number of frames. In other words, we assign r_{max} to r_K . In order to minimize wasted channel time and thereby maximize the goodput, all STAs should have the same AMPDU-TXTIME. Therefore, the selected rates r_k 's should satisfy the following relation:

$$\frac{n_k}{r_k} = \alpha \quad \text{for } k = 1, \dots, K \quad (7)$$

where α is a constant. In the second step, we use (7) to determine other r_k 's, $k = 1 \dots K - 1$. In the third step, we determine p_k 's according to the rates selected in the previous step and also channel gain and FER requirement of each STA. If total required power is not greater than the P_T the algorithm ends, otherwise we assign r_{max-1} to r_K and the aforementioned steps repeat. It worth noting that, since the rate set is a discrete set of rates the rate determined using (7) may not be available in the set. Therefore, we select the nearest rate of the set to that rate.

V. POWER ALLOCATION FUNCTION

In order to meet QoS requirement of a STA, the transmission power of its stream needs to be allocated according to MCS of that stream and that STAs instantaneous CSI. The power allocation inevitably requires a FER prediction methodology that can accurately match MCS, CSI and FER. While there are closed-form formulas for FER of single-carrier systems, the frequency selective fading makes FER estimation of a MIMO-OFDM channel a challenging task. In order to obtain an estimate of FER, we exploit the post-detection SNR of symbol received in the subcarrier l of the k th STA's channel,

which is

$$\rho_{l_k} = g_{l_k} \frac{p_{l_k}}{\sigma_k^2} \quad (8)$$

For the modulations supported by IEEE 802.11ac, there are closed-form formulas that provide a relationship between symbol SNR and bit error rate (BER) of a frequency flat narrowband channel [8]. We can apply those formulas to obtain the BER probability in each subcarrier for different modulations based on the SNR obtained using (8). For a downlink channel toward a STA, we can predict the BER of that wideband channel for each modulation by averaging its subcarriers' BERs

$$b^m = \frac{1}{L} \sum_l^L b^m(\rho_l) \quad (9)$$

where $b^m(\rho_l)$ and b^m are the BERs of the subcarrier l and the wideband channel, respectively and index m specifies a modulation scheme. In order to obtain an estimation of FER, we can apply FER upper bound provided in [9] under the assumption of binary convolutional coding and hard-decision Viterbi decoding with independent errors at the channel input. For a frame of length L_f , the FER is upper bounded by

$$1 - (1 - E_u^c)^{L_f} \quad (10)$$

where E_u^c is the union bound on the first-event error probability when the frame is transmitted using convolutional code c , which is given by

$$E_u^c = \sum_{d=d_{free}}^{\infty} a_d \cdot E_d \quad (11)$$

where d_{free} is the free distance of the code c , a_d is the total number of error events of weight d , and E_d is the probability of that error event. We can obtain E_d by

$$E_d = \begin{cases} \frac{1}{2} \cdot \binom{d}{d/2} \cdot b^{d/2} \cdot (1-b)^{d/2} \\ + \sum_{k=(d+1)/2}^d \binom{d}{k} \cdot b^k \cdot (1-b)^{d-k}, & \text{if } d \text{ is even} \\ \sum_{k=(d+1)/2}^d \binom{d}{k} \cdot b^k \cdot (1-b)^{d-k}, & \text{if } d \text{ is odd} \end{cases} \quad (12)$$

where b is the uncoded bit error probability which is given by (9). In order to determine transmission power of a stream, we allocate an initial power budget to that stream, then FER bound is computed using (10). If the FER requirement is satisfied then this power value is selected for that stream, otherwise we continue the procedure with increased power budget until FER requirement is satisfied or there is no more power budget to allocate.

VI. NUMERICAL RESULTS

In this section, we evaluate the performance of the suggested scheme using MATLAB. The channel has been modeled based on the TGn channel models. Specifically, we have used profile B (residential) of those models in our simulations. In order to make that model appropriate for IEEE 802.11ac scenarios, we have modified some of its parameters, including angle of

Table I. PHY and MAC layer parameters used in goodput computation.

parameter	value
$SIFS$	$16\mu s$
$DIFS$	$34\mu s$
T_{BO}	$67.5\mu s$
T_{PHY}	$52\mu s$
T_{BAR}	$72\mu s$
T_{BA}	$80\mu s$
T_{CS}	$1692\mu s$
M	64

arrival (AoA) and angle of departure (AoD), according to the IEEE 802.11ac task group recommendation. The system has been configured to operate with a bandwidth of $W = 20$ MHz. There are nine different MCSs, which results in transmission rates in range from 6.5 Mbps to 78 Mbps. The target FER and MPDU size are fixed at 0.01 and 1500 bytes, respectively. And the size of A-MPDU, i.e., the number of frames aggregated in each stream uniformly distributed over 1 and M . The specific parameters considered in the goodput calculation are given in Table I. The AP is equipped with four antennas. We also assume perfect channel state information at the AP, because without perfect channel knowledge, it is preferable to transmit in the single-user (SU) mode rather than in the MU mode [10]. In all the simulation runs, we set the noise variance value to the 1, for the sake of simplicity, hence in all the following figures the SNR denotes the P_T .

Figure. 2 illustrates the achieved goodput from DL-MU transmission by an AP in different SNRs. We can see that by using the suggested rate proportional power allocation mechanism, an AP can achieve a significant goodput improvement compared to case when all down link streams have the same transmission power, irrespective of the number of frames in each stream. This achievement is attributed to the balanced air time utilization by different downlink streams. For rank-deficient channels, Minimum Mean Square Error (MMSE) beamforming achieves higher performance than ZFBF, specially at low SNR. However, MMSE-BF does not provide orthogonal channels and thus power allocation techniques cannot be applied straightforwardly [5]. The highlight of our letter is presented in Figure. 3, in which ZFBF equipped with our scheme and the transmission power of downlink channels allocated proportional to the number of aggregated frames outperforms MMSE-BF in the wide range of SNRs. The reason of performance degradation of our scheme in lower SNRs is due to the noise enhancement of ZFBF.

VII. CONCLUSION

This paper presents an integrated scheme for the power allocation and rate selection problem in MU mode of 802.11ac. Using this scheme the channel time is efficiently used, and consequently better performance is achieved in terms of MAC layer throughput. We can extend this work by improving FER prediction method, and integrating the proposed scheme with a MU scheduling algorithm.

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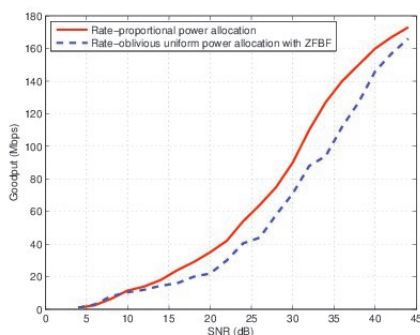


Figure 2. Goodput comparison of the proposed rate proportional power allocation and rate oblivious uniform power allocation with ZFBF.

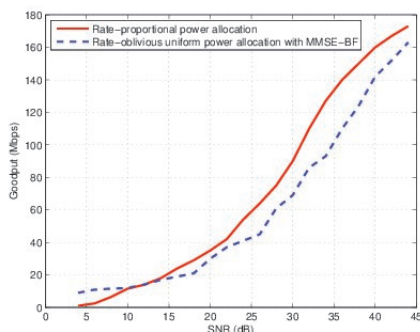


Figure 3. Goodput comparison of the proposed rate proportional power allocation and rate oblivious uniform power allocation with MMSE-BF.

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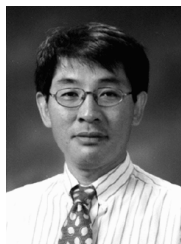
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