Energy Efficient Spatial Stream Allocation for Multi-User MIMO in 802.11ac Networks

Jeongyoon Heo, Hyung-Sin Kim, Okhwan Lee* and Saewoong Bahk
Department of Electrical and Computer Engineering,
Seoul National University and INMC, Seoul, Republic of Korea
*Samsung Electronics Co., Ltd., Suwon, 443-742, Republic of Korea
E-mail: {jrheo, hskim}@netlab.snu.ac.kr, ohlee@mwnl.snu.ac.kr, sbahk@snu.ac.kr

Abstract—In this paper, we propose a new energy efficient strategy for 802.11ac networks. 802.11ac uses multi-user MIMO (MU-MIMO) technique for throughput enhancement. When multiplexing spatial streams of different lengths, 802.11ac pads additional bits for shorter streams to equalize the sizes of all streams. The padding method incurs redundant energy consumption for a receiver while listening useless data. To alleviate the problem, we propose Energy efficient Spatial stream Allocation (ESA). When serving multiple spatial streams, ESA provide energy optimal transmission by minimizing padded bits. To this end, ESA controls both the number of antenna and modulation and coding scheme (MCS). Our simulation result reveals that ESA can significantly reduce energy consumption of receivers without throughput degradation in 802.11ac networks.

Index Terms—802.11ac, MU-MIMO, energy efficiency

I. INTRODUCTION

Recently, 802.11ac is standardized to satisfy increasing demands of high throughput (e.g., video streaming service) [1]. Compared to previous Wi-Fi standards [2], 802.11ac standard provides a set of additional technical features to improve throughput, such as multiple-input multiple-output (MIMO) up to 8 by 8, denser modulation and coding schemes (MCS), wider bandwidth up to 160 MHz by channel bonding, and larger size of frame aggregation. Especially, 802.11ac exploits multi-user MIMO (MU-MIMO) technique which can simultaneously transmit data to multiple users by spatial division using multiple antennas. It can support up to 4 users with up to 4 space time streams per user.

However, there is a trade-off between power consumption and throughput when using Wi-Fi, which has been reported by a number of previous work [3][4][5]. Recently, many portable devices are equipped with multiple antennas and support 802.11ac, including laptop computers, tablets, and even smartphones. Given that their battery life is limited, energy efficiency of Wi-Fi is a significantly important issue for portable devices since wireless cards consume large amount of energy compared to total energy consumption (e.g., <10% in current laptops and <50% in hand held devices) [6].

There have been several researches which consider energy efficiency of Wi-Fi. IEEE 802.11 standard provides power save mode (PSM) which can save energy by turning the Wi-Fi interface off when it is not in use (i.e, idle time) [1]. Agarwal et al. optimized PSM to deliver Voice over IP (VoIP) traffic while maintaining energy efficiency in idle time [7]. Zhang et al. decreased clock rate in idle listening to minimize energy cost [8]. Lee et al. minimized the active bandwidth in idle time considering a channel bonding feature in 802.11ac, which further reduces power consumption [9]. However, they deal with power consumption at a station only in idle time, making it still suffer energy inefficiency while receiving packets. Therefore, we propose the energy optimal transmission technique in receiving time which can be easily combined with aforementioned techniques in idle time and can provide energy efficiency in whole transmission time.

In this paper, we focus on energy consumption at an 802.11ac station when receiving data frames which are pre-coded via an MU-MIMO technique. We first analyze what the access point (AP) does when it spatially multiplexes data frames to simultaneously serve multiple stations using MU-MIMO. When data frame for each station has different length, AP adds pad bits at the end of shorter frames before precoding, to synchronize the length of entire multiplexed data frame to the maximum length among individual frames. The use of pad bits makes it easy to serve multiple users with different source rates using MU-MIMO. However, it incurs inefficient energy consumption at the stations which receive pad bits since they are, in fact, redundant information. Today, Wi-Fi supports various applications which have various data rate. Therefore, the data frame length for each station can be significantly different which can make the problem more severe.

To alleviate the problem, we design an energy efficient spatial stream allocation (ESA) for downlink MU-MIMO in 802.11ac networks. Specifically, the main design goal of ESA is to reduce redundant energy consumption of an 802.11ac station which comes from pad bits. It increases length of each individual data frame up to that of the spatially multiplexed frame by controlling transmission parameters such as MCS level and the number of spatial streams, which significantly reduces energy consumption at a station. Furthermore, since the removed pad bits are not valid information, ESA does not impact throughput while saving energy.

There could be another solution. When receiving an end of the data frame, the receiver can stop receiving the data. However, even in this case, ESA shows better performance if there is a sufficient amount of difference in the length of
data frame. Moreover, AP can distribute remaining resources to other stations in order to increase throughput. Lastly, ESA only considers the data reception period, which makes it easily combined with other energy saving schemes for idle time.

The remainder of this paper is structured as follows. Section II describes considered system model. Section III describes the compared schemes and proposes ESA which reduces energy consumption of receivers without throughput degradation. Section IV mathematically analyzes the performance of ESA. Then, Section V verifies the analysis and evaluates the performance of the proposed scheme by the computer simulation. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

We consider a well designed power model which provides the power consumption for receiving, idle, and transmitting state of an 802.11ac station, respectively [9]. It is derived from a real device measurement using an 802.11ac network interface card Qualcomm Atheros 9880 chipset (QCA9880) and estimates the power consumption with error rate below 2.3% on average.

Assuming that a station receives $N_{rx}$ spatial streams with $N_{rx}$ receiving antennas, power consumption for its receiving state, $P_{rx}$, is formulated as

$$P_{rx} = B(\alpha_1 N_{rx} + \alpha_2 N_{rx} \log_2 B + f_{rx}(N_{ss})) + \alpha_3 N_{ss} + \alpha_4 r + P_f$$

where $\alpha_1$, $\alpha_2$, $\alpha_3$, $\alpha_4$, and $f_{rx}$ are coefficients for receiving state model, $r$ is PHY rate (Mb/s), $B$ is active bandwidth (MHz) and $P_f$ is the default power consumption of the network interface card (mW). Power consumption for an idle state, $P_{idle}$, can be given as

$$P_{idle} = i_1 N_{rx} B + i_2 N_{ss} + P_f$$

where $i_1$ and $i_2$ are coefficients for the idle state model. Lastly, power consumption for a transmitting state, $P_{tx}$, is formulated as

$$P_{tx} = B(\beta_1 N_{rx} + \beta_2 N_{ss} \log_2 B + f_{tx}(N_{ss})) + \beta_3 N_{ss} + \beta_4 r + \beta_5 P_t + P_f$$

where $\beta_1$, $\beta_2$, $\beta_3$, $\beta_4$, $\beta_5$, and $f_{tx}$ are coefficients for the transmitting state model. We present all the aforementioned coefficients in Table I.

In this paper, we focus on the power consumption of receiving state. Specifically, the mathematical formulations show that a station’s power consumption increases with the number of receiving antennas $N_{rx}$, the number of spatial streams $N_{ss}$, and PHY rate $r$ (i.e., MCS level) in receive state.

III. PROPOSED SCHEME - ESA

This section explains two conventional schemes and discusses their drawbacks. Then, we suggest a new scheme for power saving, so called energy efficient spatial stream allocation (ESA). Specifically, we use Fig. 1 to describe the differences of ESA compared to the pre-existing schemes, which shows an operation example when an 802.11ac AP sends different length of downlink data to two stations, each of which has four antennas, using MU-MIMO.

A. Highest Goodput (HG)

An 802.11ac station always turns on all of its antennas by default even when it is not needed. Thus, it wastes a significant amount of power while achieving highest goodput. In this paper, we call the basic mode without energy saving as highest goodput (HG). Fig. 1(a) illustrates an example of HG operation. It shows that the stations turn on all the 4 antennas to receive packets even though they need only three ones since the AP transmits three spatial streams, resulting in waste of energy.

<table>
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Fig. 1. An operation example of HG, SMPS, and ESA when an AP sends different length of data to two stations, each of which has four antennas, using MU-MIMO.
B. Spatial Multiplexing Power Save (SMPS)

IEEE 802.11n standard specifies the spatial multiplexing power save (SMPS) [2] feature to reduce power consumption at stations. SMPS uses only one antenna in idle time to minimize the power consumption. When a station receives packets, SMPS makes the station to activate the required number of antennas (i.e., same as the number of spatial streams). As IEEE 802.11n standard does not provide MU-MIMO, we modify the SMPS to support MU-MIMO. In modified SMPS, All receivers only turn on their antennas as much as needed. That is, unlike HG, SMPS can turn off some of their antennas which are not used during packet reception. Although, SMPS can reduce power consumption in both idle and receiving time, we focus on the process of SMPS in receiving time to compare with ESA.

Fig. 1(b) shows an example of SMPS procedure. We can notice that SMPS allows each station to turn off one antenna and use only three antennas to receive data streams, which enables power saving at the stations.

However, we point out that SMPS is not optimized to support power saving in 802.11ac MU-MIMO architectures. Specifically, given that an AP has a different length of data frame for each user (after applying the determined MCS level and the number of spatial streams), it sets the length of spatially multiplexed data frame as the maximum length among individual data frames. Before encoding the multiplexed data frame for MU-MIMO, AP adds pad bits at the end of other (individual) data frames to synchronize their lengths to the maximum one. In this case, each station is required to turn on its antennas until the end of multiplexed data frame even when it finishes receiving its data earlier, which incurs unnecessary power consumption.

Given that 802.11ac uses a frame aggregation technique which makes extremely long data frames (i.e., 5.484 ms), the amount of pad bits (i.e., difference between data frame length) is not negligible when AP has different source rate for each station. It implies that current energy saving techniques need to be improved to further reduce energy consumption in an MU-MIMO architecture of 802.11ac.

C. Proposed Energy Efficient Spatial Stream Allocation (ESA)

Previous Section reveals that 802.11ac MU-MIMO suffers energy waste when AP spatially multiplexes data frames with different length. To address the challenge, we propose a new power saving feature for 802.11ac MU-MIMO, called ESA, which controls the number of spatial streams and the MCS order of each station to minimize the power consumption of stations in MU-MIMO without throughput loss.

Specifically, we aim to minimize the amount of pad bits for shorter individual data frames which cause energy waste. That is, ESA increases the length of short data frames until they reach the length of multiplexed frame by adjusting MCS level with the number of receiving antennas and spatial streams (i.e., \( r, N_{rx}, \) and \( N_{ss} \)). Given that those parameters are associated with power consumption at a receiver as described in Section II, using lower MCS level and fewer number of antennas or spatial streams significantly saves energy during receiving state. Furthermore, the increase in data frame length does not impacts on throughput since it maintains the length of multiplexed frame and removes only redundant pad bits.

Fig. 1(c) shows an operation example of the ESA procedure, where AP transmits different length of data frames to two stations using MU-MIMO. Even though the AP transmits data using three spatial streams for both two users when considering channel information, ESA additionally notices the different frame length for each station and increases the frame length for station 2 until it reaches a maximum value which is less than or equal to that of multiplexed data frame. As a result, AP reduces the number of spatial streams for station 2, from three to one, which improves energy efficiency.

Overall, ESA can reduce energy consumption without throughput degradation.

IV. ANALYSIS

In this section, we mathematically show the impact of ESA by calculating the expected power gain, \( E[Gain] \), in data receiving time. For the analysis, we consider a downlink transmission scenario where an AP transmits data frames to two stations using MU-MIMO. Assuming that the AP randomly selects a source rate for each user between \( S_{min} \) and \( S_{max} \) (with uniform distribution), the probability that the AP selects \( s \) for source rate, \( p(s) \), is formulated as

\[
p(s) = \frac{1}{S_{max} - S_{min}}. \tag{4}
\]

For mathematical tractability, we assume that the AP generates a periodic traffic for each user with the given source rate, which makes data frame length for each user proportional to its source rate.

We arrange all combinations of the number of antennas and MCS level as an decreasing order of transmission rate. Assume that there are \( N \) combinations. We define \( n \) as the combination number, which indicates that use of higher \( n(1 \leq n \leq N) \) results in lower transmission rate. Letting \( r(n) \) be the PHY rate when using \( n, r(n_1) > r(n_2) \) when \( n_1 < n_2 \).

Since we do not consider channel error, the AP can always send packets with \( r(1) \), which is use of the maximum number of spatial streams and MCS order. These assumptions help solely extract the impact of ESA. Lastly, we define \( P_{rx}(n) \) as the power consumption at a station while receiving data frame which is transmitted using \( n \). \( P_{rx}(n) \) can be calculated from equation (1) in Section II.

Letting \( s_1 \) and \( s_2 \) be the source rate of station 1 and 2, respectively, length of the spatially multiplexed data frame is \( max(s_1,s_2) / r(1) \). Then, average power consumption at a station when using HG, \( E[P_{HG}] \), can be expressed by

\[
E[P_{HG}] = 2 \int_{S_{min}}^{S_{max}} \int_{S_{min}}^{S_{max}} p(s_1) p(s_2) s_2 P_{rx}(1) r(1) ds_2 ds_1 \tag{5}
\]

\[
= P_{rx}(1) (2S_{max}^2 - S_{max}S_{min} - S_{min}^2) \frac{3r(1)(S_{max} - S_{min})}{3}.
\]
In our analytical model, SMPS consumes the same power during data reception since both schemes use \( n = 1 \), which makes \( E[P_{\text{SMPS}}] = E[P_{\text{HG}}] \).

When \( s_2 > s_1 \), ESA sends data frames to station 2 with \( n = 1 \), same as HG and SMPS, and thus station 2 consumes \( E[P_{\text{HG}}] \).

However, unlike the conventional schemes, ESA increases \( n \) of the data frame for station 1 (i.e., shorter frame) to increase its length up to that of data frame for station 2. Thus, power consumption at a station using ESA, \( E[P_{\text{ESA}}] \), can be represented as

\[
E[P_{\text{ESA}}] = \frac{E[P_{\text{HG}}]}{2} + \int_{s_{\text{min}}}^{s_{\text{max}}} p(n|s_1,s_1<s_2) \frac{s_2 P_n(n)}{r(1)} ds_1
\]

where \( p(n|s_1,s_1<s_2) \) is the probability that AP selects \( n \) for transmission of the shorter frame when the source rate of the shorter frame \( s_1 \) is given.

To analyze the effect further, we focus on the ratio between \( s_1 \) and \( s_2 \) (i.e., \( s_1/s_2 \) or \( s_2/s_1 \)) since ESA can use \( n \) for station 1 when

\[
1 + \alpha_n \leq \frac{s_2}{s_1} < 1 + \alpha_{n+1}
\]

where \( \alpha_n (n = 1,\ldots,N+1) \) is a threshold given that \( \alpha_0 = 0 \) and \( \alpha_{N+1} = \infty \). Then, \( p(n|s_1,s_1<s_2) \) can be calculated as

\[
P(n|s_1,s_1<s_2) = P\left(1 + \alpha_n \leq \frac{s_2}{s_1} < 1 + \alpha_{n+1} \mid s_1,s_1<s_2\right)
\]

\[
P(n|s_1,s_1<s_2) = \begin{cases} \frac{(\alpha_{n+1} - \alpha_n) s_1}{s_{\text{max}} - s_{\text{min}}}, & \text{for } s_{\text{min}} \leq s_1 < \frac{s_{\text{max}} - s_{\text{min}}}{1 + \alpha_{n+1}} \\ \frac{(\alpha_{n+1} - \alpha_n) s_1}{s_{\text{max}} - s_{\text{min}}}, & \text{for } \frac{s_{\text{max}} - s_{\text{min}}}{1 + \alpha_{n+1}} \leq s_1 < \frac{s_{\text{max}} - s_{\text{min}}}{1 + \alpha_{n+1}} \\ 0, & \text{otherwise.} \end{cases}
\]

Finally, \( E[P_{\text{ESA}}] \) can be represented as equation (6) and the expected power gain, \( E[\text{Gain}] \) can be calculated as

\[
E[\text{Gain}] = \frac{E[P_{\text{compare}}] - E[P_{\text{ESA}}]}{E[P_{\text{compare}}]}. \tag{10}
\]

To see the impact of the performance according to the source rate range, we plot Fig. 2 from equation (10). We set a network with two stations with 3 antennas respectively, and

we use MCS 0 to 7 and 20 MHz bandwidth. Table II shows \( N(=15) \) combinations of the number of antennas and MCS levels with the related related threshold \( \alpha_n \). Fig. 2 shows the \( E[\text{Gain}] \) when the source rate range (i.e., \( S_{\text{max}} - S_{\text{min}} \)) increases. Specifically, we set the average source rate of each user to 100 Mbps and set \( S_{\text{min}} = 100 - \text{gap}/2 \) and \( S_{\text{max}} = 100 + \text{gap}/2 \). We can notice that \( E[\text{Gain}] \) increases when source rate gap increases.

### V. PERFORMANCE EVALUATION

In this section, we evaluate the performance of ESA by the MATLAB-based computer simulations. We consider a network comprising an AP with 8 antennas and two stations each of which has three antennas. The AP exploits transmission power of 20 dbm and a station exploits that of 15 dbm. Moreover, we consider channel bandwidth of 20MHz and noise magnitude of -95 dbm. We use TGac channel model to generate SNR [10]. Table III shows the parameters used for our simulations. AP generates data frames for each station with Poisson distribution during the simulation time with given source rate. Lastly, we calculate the average energy efficiency and throughput of the three schemes, HG, SMPS and ESA in various environments.

#### A. Effect of source rate difference

First, we show the performance of ESA according to the source rate difference between the two stations. Stations are placed on a circle around the AP with radius of 10 m. We set the source rate of the first station to 150 Mbps and vary the source rate of the second station from 0.1 to 1 times of the first station.

Fig. 3(a) shows the energy efficiency (J/bit) of HG, SMPS and ESA. We first observe that ESA always provides lower energy consumption than competitive schemes. Furthermore, the performance gain of ESA increases with the difference between source rates of two stations. For example, when the source rate of the second station is half of that of the first station, ESA consumes 14.09% less power than HG and 13.49% less power than SMPS. When it becomes 0.1 times smaller than that of the first station, ESA can reduce power consumption 21.42% more than HG and 18.82% more than SMPS. We notice that ESA consumes slightly lower energy even when two stations have same source rates. This is because use of the same source rate does not guarantee the same number of packets in the queue at every time when the packet arrives with Poisson distribution.
Throughput (Mbps)

Energy efficiency (J/bit)

Gain (%)

100
150
200
250
300
50
10
12
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1
0
0.2
0.4
0.6
0.8
1

Fig. 2. $E[Gain]$ in various source rate gap between stations

Fig. 3(b) shows network throughput of HG, SMPS and ESA. It reveals that all of the three schemes always provide the same throughput. It is because ESA removes only redundant pad bits to reduce power consumption, which allows it to maintain throughput.

Now we consider a more general case where AP randomly selects source rate for each station in the region of $(100 - \text{gap}/2, 100 + \text{gap}/2)$ before a simulation starts. We run the simulation 100 times and calculate the average performance. We aim to find out the impact of source rate range with the given average source rate (i.e., 100 Mbps) on the performance of ESA. Stations are placed on a circle around the AP with radius of 10 m.

Fig. 4 shows power consumption gain of ESA compared to competitive schemes. Similar to the analytic results in section IV, the simulation results show that performance gain of ESA increases with the source rate range. Furthermore, we can notice that even with source rate gap 0 (i.e., same source rate) ESA shows about 15% energy gain. Even with same source rate, there can be the different number of packets in the queue destined to each user, because packets arrive with poisson distribution.

**B. Effect of channel errors**

Finally, we investigate the effect of channel condition of the performance of ESA by randomly deploying stations within the circle of radius $d$ where the AP is located in the center. Fig. 5 shows energy efficiency of three schemes with varying the radius $d$. For each $d$, we run 100 simulations where source rate of a station is randomly selected between 20 Mbps and 200 Mbps.

When $d$ is small, performance of SMPS is similar to that of HG, as shown in Fig. 4. As $d$ increases, performance of SMPS becomes similar to that of ESA since it allows a station to turn off some of its antennas when $n$ is large due to bad channel conditions. It is also revealed that ESA outperforms the other two schemes regardless of the channel conditions, while the performance gap compared to SMPS decreases with $d$. For example, when $d = 5m$, ESA consumes about 18.83% less energy per bit than HG and 14.76% less than SMPS. However when $d = 50m$, ESA consumes 26.61% less energy per bit than HG and 9.57% less than SMPS.

**VI. Conclusion**

We have tackled an energy consumption problem of 802.11ac network when serving multiple users with various source rates. Specifically, 802.11ac uses padding method to synchronize the length of data frame for each station to support...
MU-MIMO, which incurs redundant energy consumption at a station while receiving pad bits. To address the problem, we propose ESA which adjusts the number of spatial streams and MCS level of shorter data frames to optimize energy consumption. Each station can reduce the energy consumption during data reception by using the fewer number of antennas and lower MCS level. Furthermore, ESA does not impact on throughput since it removes only redundant pad bits to enhance energy efficiency. We evaluate the performance of ESA by computer simulations. Specifically, our results reveal that the performance improvement increases with source rate range.

Given that today’s Wi-Fi needs to support various kinds of applications in practice, from a simple text delivery to a high quality video streaming, ESA can allow 802.11ac to spatially multiplex various data frames without energy waste.

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