Practical Antenna Selection for WLAN AP

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Abstract—Antenna selection, a cost-effective way to enhance network performance, has been employed in a limited manner in wireless local area networks (WLANs) due to the lack of channel information at the transmitter. In this paper, a practical antenna selection system without using channel information is proposed. We first describe the practical issues of antenna selection system for infrastructure-based WLANs, and then, analyze its characteristics through an extensive measurement study. Based on that, we propose antenna selection algorithms of access point (AP) for both (1) unicast transmission and (2) multicast transmission and reception. The proposed algorithms are comparatively evaluated using prototype implementation in a commercial AP. It is demonstrated that the proposed algorithms achieve up to 34% throughput gain and 54% frame error rate reduction for unicast and multicast transmissions, respectively.

I. INTRODUCTION

Multiple-input multiple-output (MIMO) technology is an indispensable part of wireless local area networks (WLANs) because of increased data rate by spatial multiplexing and reliability enhancement by spatial diversity. Unfortunately, there is a trade-off between spatial multiplexing and diversity, i.e., maximum spatial multiplexing gain is achievable with the sacrifice of diversity gain, and vice versa [1]. Therefore, extra antennas are needed to increase diversity gain along with a certain degree of multiplexing gain. However, there are two main limitations in increasing the number of antennas, namely, the hardware costs of radio frequency (RF) chains (including RF power amplifier and analog-to-digital/digital-to-analog converter, etc.) for each antenna and the computational complexity for signal encoding and decoding process.

Antenna subset selection is a cost effective way to achieve diversity gain without such limitations. By employing more antennas than RF chains and adaptively connecting each RF chain to one of the available antennas, diversity gain can be obtained without loss of multiplexing gain. It was proved that such antenna subset selection retains the same degree of diversity compared with the full-complexity system, i.e., the system with the same numbers of antennas and RF chains [2].

There has been extensive research in antenna subset selection algorithms [3–9]. The authors in [3–6] utilize instantaneous channel state information (CSI) to select an optimal antenna subset. Similarly, statistical CSI is utilized for the antenna subset selection in [7–9]. However, off-the-shelf WLAN devices do not implement CSI feedback functionality due to its significant overhead, thus limiting the applications of the proposed schemes in [3–9]. To the best of our knowledge, there is no research paper in the literature that proposes antenna subset selection algorithm without utilizing CSI.

Meanwhile, a couple of patents deal with antenna subset selection system without using CSI. In [10], an antenna subset is selected using a trial-and-error approach, i.e., a single antenna subset is selected and used until a transmission failure occurs. In [11], an optimal antenna subset is determined based on statistical information. The information is obtained by probing, i.e., periodically transmitting frames using different antenna subsets. Although the patents describe the example procedures, detailed algorithms and performance evaluations are not presented due to the nature of patent.

The main purpose of this paper is to develop a practical antenna subset selection method for off-the-shelf devices without any modification or additional requirement of IEEE 802.11 standard and WLAN chipsets. We propose antenna subset selection algorithms of access point (AP) (a) for unicast transmission and (b) for multicast transmission and reception. Compared with the existing schemes in the literature, the main advantages of our proposed algorithms are:

1) Practicality: The proposed algorithms are designed to be applicable to commercial WLAN chipsets, which utilize multiple retry chains for a packet transmission. In addition, only currently available information in WLANs, e.g., frame success ratio (FSR), is used. The practicality is proved by a prototype implementation of the proposed algorithms in a commercial AP.
2) Robustness: The best and the second best antenna subsets are used alternatively to achieve diversity gain, thus reducing the occurrence of consecutive transmission failures.
3) Self-regulation: The frequency of probing is automatically adjusted depending on channel condition, i.e., more probing for bad channel and less probing for good channel, thus minimizing probing overhead.

The rest of the paper is organized as follows: Section II describes the current status of infrastructure-based WLAN. We demonstrate the potential for network performance improvement via antenna selection through measurements in Section III. Then, we propose practical antenna selection algorithms for transmission and reception of AP in Section IV, and then evaluate the performance of the algorithms through an extensive measurement study in Section V. Finally, we draw the conclusion in Section VI.

II. SYSTEM DESCRIPTION

In this section, we first describe the characteristics of off-the-shelf devices, which constitute infrastructure-based WLAN. Then, we describe the antenna selection system.
MPDU Drop

downlink (DL) CSI at an AP, namely, implicit feedback

Antenna selection means antenna combination selection for the connected to the corresponding RF chain, and we use the term, denoted by a combination, which consists of the antennas each chain is connected to the corresponding RF chain. As we select, specifically, one of the antennas confined to an RF transmission descriptor. Different from general antenna subset of data streams.

AP always utilizes all the RF chains regardless of the number many WLAN chipsets including QCA chipsets use spatial thus allowing to use cheaper power amplifier. Accordingly, each RF chain can share the burden for the maximum power, divided into the employed RF chains, the power amplifier of advantage related to power amplifier. Since the total power is it is replicated and transmitted through three RF chains with is used to map a single data stream to three RF chains, i.e.,

\[
\begin{align*}
\text{Chain 0:} & \quad (R_0, C_0, A_0) \\
\text{Chain 1:} & \quad (R_1, C_1, A_1) \\
\text{Chain 2:} & \quad (R_2, C_2, A_2) \\
\text{Chain 3:} & \quad (R_3, C_3, A_3)
\end{align*}
\]

MPDU Drop

\[
\begin{align*}
R: & \quad \text{data rate} \\
C: & \quad \text{number of attempts} \\
A: & \quad \text{antenna configuration}
\end{align*}
\]

\[
\begin{align*}
\text{Fig. 1. Transmission parameters for multiple retry chains.}
\end{align*}
\]

- **A. Characteristics of Off-the-Shelf Devices**

  There are four characteristics of off-the-shelf devices which should be considered for practical antenna selection systems.

  - **Multiple retry chains:** Most commercial WLAN devices use multiple retry chains. For example, Qualcomm Atheros (QCA) WLAN chipsets use four different retry chains. A transmission descriptor is configured for each MAC protocol data unit (MPDU) and describes the transmission parameters of each retry chain, i.e., the data rate \( (r_1) \), the maximum number of tries \( (n_0) \), and the antenna configuration \( (c_0) \) for retry chain \( i \), as shown in Fig. 1. The first transmission of an MPDU uses data rate, \( r_0 \), and antenna configuration, \( c_0 \). If the transmitter does not receive the corresponding acknowledgement (ACK) for the first transmission, the MPDU is retransmitted up to \( (n_0 - 1) \) times with \( r_0 \) and \( c_0 \). If all \( n_0 \) (re)transmissions fail, then \( r_1 \) and \( c_1 \) are used for the next \( n_1 \) retransmissions, and \( r_2 \) and \( c_2 \) are sequentially used until the packet is successfully transmitted or dropped.\(^1\)

  - **Spatial expansion:** Data streams can be expanded via matrix multiplication to produce the input to all the RF chains, namely spatial expansion. For instance, matrix \( D = \frac{1}{\sqrt{3}} [111]^T \) is used to map a single data stream to three RF chains, i.e., it is replicated and transmitted through three RF chains with reduced power. With the spatial expansion, the AP can take an advantage related to power amplifier. Since the total power is divided into the employed RF chains, the power amplifier of each RF chain can share the burden for the maximum power, thus allowing to use cheaper power amplifier. Accordingly, many WLAN chipsets including QCA chipsets use spatial expansion by default. In this work, thus, we assume that the AP always utilizes all the RF chains regardless of the number of data streams.

  - **Antenna subset selection:** QCA chipsets adopt antenna subset selection using RF switches which connect antennas to RF chains according to the antenna configuration in the transmission descriptor. Different from general antenna subset selection, specifically, one of the antennas confined to an RF chain is connected to the corresponding RF chain. As we assume spatial expansion, therefore, an antenna subset can be denoted by a combination, which consists of the antennas each connected to the corresponding RF chain, and we use the term, antenna combination, hereafter. In this paper, furthermore, antenna selection means antenna combination selection for the RF chains.

  - **No CSI feedback:** There are two methods for obtaining downlink (DL) CSI at an AP, namely, implicit feedback

\(^1\)If all the retransmission attempts fail, the MPDU will be dropped.

- **B. Antenna Selection for WLAN AP**

  - **Problem statement:** For a practical antenna selection system with off-the-shelf devices, we only consider antenna combination selection of AP side in infrastructure-based WLAN.\(^2\) We assume that the number of RF chains is \( M \) and each RF chain has \( L \) antennas, and hence, there are total \( L^M \) combinations, one of which can be selected for transmission/reception. For the ease of our explanations, we consider the case of \( M=3 \) and \( L=2 \) as shown in Fig. 2, so there are 8 possible combinations.

  - **Antenna selection of AP can be classified into two cases, namely, transmit antenna selection and default antenna selection. Transmit antenna is for unicast transmission which aims to a specific target station as shown in Figs. 2(a) and 2(b), while default antenna is used for the reception of UL frames\(^3\) or the transmission destined to multiple stations, e.g., multicast transmission and beacon transmission, as shown in Fig. 2(c). Therefore, default antenna combination should be selected considering all the associated stations of an AP.

  - **Without CSI feedback, only two types of information are available for antenna selection, namely, frame success ratio (FSR) via ACK and received signal strength indicator (RSSI) of UL frames. The antenna selection should be performed in an open-loop manner using the information. However, the RSSI of UL is significantly different from that of DL due to the asymmetry between the RF chains of AP and stations as well as receiver combining methods, as detailed in Section III. For

\(^2\)Typically, APs have more RF chains than other WLAN devices.

\(^3\)Intuitively, the selected transmit antenna combination is used for the corresponding ACK frame reception while the default antenna combination is used for any other reception since AP does not know the target station in advance of reception.
this reason, the RSSI of UL cannot be utilized for antenna selection, and AP should select transmit/default antenna based on the frame success statistics.

**Mathematical description:** As we assume spatial expansion, data symbol received at a station, when AP transmits a single data stream through antenna combination \( c = (a_1, a_2, \ldots, a_M) \), can be expressed as:

\[
y_c = y(a_1, a_2, \ldots, a_M) = h x + n = \sum_{i=1}^{M} g_{i,a_i} h_{i,a_i} x + n,
\]

where \( a_i \) is the selected antenna index for RF chain \( i \) \((a_i \in \{0, 1, \ldots, L-1\})\), and \( n \) is additive white Gaussian noise (AWGN) with the variance equal to \( N_0 \). \( g_{i,a_i} \) and \( h_{i,a_i} \) are the antenna gain and fading coefficient of RF chain \( i \) with \( a_i \), respectively. We assume independent Rayleigh fading channel for each antenna.\(^4\) Therefore, \( h_{i,a_i} \) is a complex Gaussian random variable with zero mean and variance, and there is no correlation among different antennas. It should be noted that the superposed channel \( h \) is also a complex Gaussian random variable with zero mean and variance, equal to \( \sum_{i} g_{i,a_i}^2 \), thus making \( h \) a Rayleigh fading channel.

The signal-to-noise ratio (SNR) at the receiving station, i.e., SNR of DL signal, is given by

\[
SNR_{DL} = P_s \sum_{i=1}^{M} g_{i,a_i} h_{i,a_i}^2 / N_0,
\]

where \( P_s \) is the average power of the data symbol \((x)\) at the receiving station.

AP selects a default antenna combination to receive UL signal, and the received variance at the AP can be also expressed as (1). Unlike the DL signal, however, the AP can conduct a receiver combining such as maximal ratio combining (MRC) or equal gain combining (EGC) to achieve diversity gain. In this paper, we assume MRC is used, so the SNR of UL signal at the AP is given as

\[
SNR_{UL} = P_s \sum_{i=1}^{M} |g_{i,a_i} h_{i,a_i}|^2 / N_0.
\]

The antenna gain, \( g_{i,a_i} \), varies depending on the target station and its position since different antennas have different radiation patterns. Therefore, by choosing the antenna combination which consists of the antennas giving maximum gain for each RF chain \( i \) as

\[ c_{max} \triangleq (a_{max,1}, \ldots, a_{max,M}), \]

where \( a_{max,i} = \arg \max_{a_j} g_{i,a_j} \), the average SNRs of both UL and DL signals are maximized. Meanwhile, DL SNR is more vulnerable to fading than UL SNR as shown in (2) and (3). It is because receiver combining of UL helps make constructive superposition of received symbol while DL cannot avoid destructive superposition. Although we only derive (1)–(3) for single stream, it is obvious that \( c_{max} \) also gives the maximum average SNR for multiple streams.

In this paper, the antenna selection is aimed at finding \( c_{max} \) which maximizes throughput in a long-term average sense. The long-term average throughput does not depend on the instantaneous fading coefficient \((h_{i,a_i})\), because the mean of \( h_{i,a_i} \) is one for all \( a_i \)'s. The instantaneous CSI, therefore, is not essential for the antenna selection.

### III. Measurement Studies

This section demonstrates the potential for performance improvement by antenna selection and investigates several considerations for designing antenna selection algorithms.

#### A. Throughput with Different Antenna Combinations

We first measure throughput according to antenna combination to gauge the performance gain from the antenna selection.

The measurements are carried out in an office environment shown in Fig. 4. Samsung WEA303 AP and Samsung Galaxy S3 smartphones are used. WEA303 supports 802.11n MIMO up to 3 streams with 3 RF chains and 2 antennas for each RF chain [14] while Samsung Galaxy S3 supports 802.11n single stream only [15]. The station is placed at 6 different positions as shown in Fig. 4, where the position index represents the ranking of average RSSI at the position. Using IxChariot 7.3 [16], DL UDP traffic with 1460 bytes payload size is generated, and throughput is measured for 10 seconds. We repeat this measurement 8 times by switching antenna combination to compare the throughput according to the 8 different antenna combinations \((L_M = 2^3 = 8)\). One iteration consists of these 8 measurements, and 20 iterations are carried out at each position. During the measurement, no or just a single person is sitting in the office to make a stationary environment, and we
maintain this condition for all the measurements throughout this paper. The AP is configured to use channel 48, which is clean without any interference, and detailed configuration is described in Table I.

Fig. 3 shows the average throughput for each iteration at three different positions. The measurements for 8 different antenna combinations in the same iteration are carried out at almost same time, and hence, can be construed as a transient performance according to the combination. Fig. 3(a) shows the result for position 5, where the channel for all antenna combinations is stable. Therefore, the throughput for each antenna combination does not fluctuate much according to the iterations. At the position, antenna combination ‘111’ achieves the highest throughput while combination ‘010’ obtains the lowest throughput regardless of the iterations. This shows that selecting a proper antenna combination can significantly enhance throughput performance at certain positions. On the other hand, Figs. 3(b) and 3(c) presenting the results for positions 6 and 3 show temporal variation of throughput. At position 6, for instance, the throughput of antenna combination ‘101’ varies from 5 Mb/s to 24 Mb/s over iterations. Whether the channel is stable or not, there exists the best antenna combination at an iteration and it depends on the station’s position, e.g., ‘111’ at position 5 and ‘100’ at position 3 (except iteration 3). Furthermore, the best combination of previous iteration can show degraded throughput compared with other combinations due to fading, e.g., the throughput of ‘011’ at position 6 rapidly decreases after iteration 12. It is because each antenna combination could experience fading due to destructive superposition in DL as described in Section II, and there is no exception for the best combination.

The throughputs and RSSIs measured at 6 positions are summarized in Table II. Avg. and std. represent the average and standard deviation of performances out of 8 antenna combinations, respectively. Last row shows the throughput gain of the best antenna combination over the average throughput of 8 antenna combinations. According to the table, the throughput gain from antenna selection highly depends on the station’s position. At positions 3, 5, and 6, the gain is above 20% while the relatively negligible gain is observed at the other positions. By comparing position 1 with 5, and position 3 with 4, we observe that the positions with high throughput gain are characterized by low average RSSI and high standard deviation of RSSI. This shows that, at a certain position, a significant performance gain can be achieved by selecting a proper antenna combination.

**B. DL/UL Link Analysis**

Next, we study the relationship between UL and DL based on measurement results. We carry out a similar measurement as in Section III-A, but with different station positions. At each position, DL and UL UDP traffic are alternatively generated for 10 seconds. Similarly, 10 iterations are conducted at each position and the measurement result is summarized in Table III. In the top side, Pearson’s correlation coefficients $r$ and p-values$^5$ from 80 pairs, i.e., 8 antenna combinations $\times$ 10 iterations, of (UL RSSI, DL throughput) are displayed for each position. In terms of every position, $r$ is observed to have the value close to zero rather than one as well as the high level of $p$. This indicates we cannot say there is any correlation between UL RSSI and DL throughput. UL RSSI, therefore, is not a proper metric for transmit antenna selection.

$^5$p-value represents the reliability of the obtained correlation, and p-value under 0.01 means significantly high reliability.
On the other hand, there exists a distinct correlation between DL throughput and UL throughput as displayed in the bottom side, i.e., $r$ close to 1 and $p$ under 0.1. This result demonstrates that the antenna combination with good DL performance is likely to work well for UL as expected by the mathematical analysis in Section II. That is, according to (2) and (3), although the instantaneous RSSI values of DL and UL (RSSI=SNR-$N_0$) can be different, the combination $c_{\text{max}}$ in (4) gives the maximum average SNR for both DL and UL, thus giving the throughput correlation between DL and UL.

### IV. Proposed Antenna Selection Algorithm

In this section, we propose antenna selection algorithms to determine AP’s transmit and default antenna combinations. As shown in Section III, UL RSSI is not a proper metric to be used for antenna selection. Therefore, the proposed algorithms utilize only the frame success statistics, gathered based on ACK reception.

#### A. Transmit Antenna Selection

The key observations in Section III for transmit antenna selection are twofold. First, there exists difference of performances between antenna combinations, and the best one could vary depending on the station (position). Second, as the wireless channel fluctuates over time, even the best combination can experience fading, thus resulting in considerable throughput degradation.

**Best1Probe**: Focusing on the first observation, we establish a baseline algorithm which finds the best antenna combination using frame success ratio (FSR) statistics. The antenna selection method in [11] performs probing, when it is not a retransmission, to gather statistics of antenna configurations which are not being currently used, and updates the best antenna configuration based on FSR. We construct the baseline algorithm following the basic procedure in [11], and referring to Minstrel rate control algorithm [17] for the detailed operation.

The procedure of the baseline algorithm, called Best1Probe, is described in Algorithm 1. Basically, FSR of the currently used antenna combination, i.e., the best combination ($c_{\text{best}}$), and FSR of probing antenna combination ($c_{\text{probe}}$) are gathered during a time interval ($T_{\text{interval}}$). At the end of $T_{\text{interval}}$, the combination which has higher FSR is determined as $c_{\text{best}}$ for the next $T_{\text{interval}}$. Every $T_{\text{interval}}$, $c_{\text{probe}}$ is changed randomly or sequentially to find the best antenna combination among all possible combinations. Data rates of retry chains can be different from each other, so FSRs of different antenna combinations should be compared not across the retry chains but only in the same retry chain. Therefore, FSRs of the two combinations are measured and compared only for retry chain 0 which is mostly tried with a proper rate control.

As explained in Section II, antenna combinations for four retry chains of a packet can be configured by transmission descriptor. We define antenna combination series, $S$, as the configured four antenna combinations, $(c_0, c_1, c_2, c_3)$. The baseline algorithm finds only the best antenna combination, so $S$ is configured to $(c_{\text{best}}, c_{\text{best}}, c_{\text{best}}, c_{\text{best}})$ for normal case and $(c_{\text{probe}}, c_{\text{best}}, c_{\text{best}}, c_{\text{best}})$ for probing.

**Best2Probe**: We should be reminded of the second observation that the best combination can experience fading since DL cannot obtain diversity gain by receiver combining. In other words, using only the best antenna combination for transmission can be vulnerable to fading. Obviously, one way to obtain diversity gain for DL is to use different antenna combinations by turns.

To investigate the diversity gain from using different antenna combinations alternatively, we exploit a well-known metric to assess diversity techniques, average fade duration (AFD), which quantifies how long a channel gain stays below a certain fading threshold. AFD of the case when $N$ antenna combinations are alternatively used ($AFD_{\text{au}}$) approximates AFD of selection combining ($AFD_{\text{sc}}$), where selection combining selects the antenna which has the maximum channel gain among $N$ candidates, and the relation can be expressed as

$$AFD_{\text{au}} \leq AFD_{\text{sc}} + N \Delta t,$$

where $\Delta t$ is the time interval of changing combinations. The inequality holds because the antenna combination which has the maximum channel gain will be used within $N \Delta t$ for
the alternative usage case. If $N\Delta t$ is negligible, the diversity gain comparable to selection combining can be achieved. By configuring different antenna combinations for different retry chains, the antenna combination will be changed within a couple of frame transmissions which is typically few milliseconds or less, so we can make $N\Delta t$ significantly negligible with small $N$.

AFD of selection combining is derived in [18] for $N$ Rayleigh fading channels, and shown in Fig. 5. For balanced case, i.e., average channel gains are equal for all $N$ channels, AFD is inversely proportional to $N$. For instance, alternative usage of two antenna combinations decreases AFD by 50% compared with one antenna combination. For imbalanced channels, i.e., they exist an imbalance between average channel gains of antenna combinations, the AFD reduction due to the diversity gain decreases as the imbalance increases.

Based on the observations, we propose an algorithm, called Best2Probe, which utilizes the best and 2nd best antenna combinations alternatively. Following the basic procedure of Best1Probe, FSRs of the best ($c_{\text{best}}$), the 2nd best ($c_{\text{2nd}}$), and probed combination ($c_{\text{probe}}$) are measured during $T_{\text{interval}}$, and the best and 2nd best combinations are determined for the next $T_{\text{interval}}$. To compare $c_{\text{best}}$ and $c_{\text{2nd}}$, $S$ is configured to either $(c_{\text{best}},c_{\text{2nd}})$ or $(c_{\text{2nd}},c_{\text{best}})$ alternatively. Moreover, for probing, $c_0$ is configured to $c_{\text{probe}}$ for 10% of the packets. The detailed algorithm is described in Algorithm 2.

Expected problems are the reduction in diversity gain due to the imbalance of channels and the obvious performance degradation when the 2nd best combination is considerably worse than the best one. As described in lines 14–18, therefore, when the gap between the FSRs of the best and 2nd best combinations is larger than a threshold ($D_{\text{thr}}$), only the better one is used for retry chain 0 during the remaining time of $T_{\text{interval}}$.

**Best2Match**: There is a downside of probing at retry chain 0 as Best1Probe and Best2Probe do. A randomly or sequentially selected $c_{\text{probe}}$ inevitably degrades the performance because it is less guaranteed to have a good channel condition than the best and 2nd best antenna combinations.

Thus, we propose a revised algorithm, called Best2Match, which carries out probing in retry chain 1 and 2 instead of retry chain 0. Since antenna combinations should be compared in the same retry chain, two of the three antenna combinations are compared in each retry chain among retry chains 0–2, and then the performance ranking is determined by the three comparisons as league match. Thus, we configure $S$ to two types as $S_{\text{best}}=(c_{\text{best}},c_{\text{2nd}},c_{\text{probe}},c_{\text{best}})$ and $S_{\text{2nd}}=(c_{\text{2nd}},c_{\text{probe}},c_{\text{best}},c_{\text{2nd}})$ as in Algorithm 3. By using the two types of configuration alternatively, $c_{\text{best}}$ and $c_{\text{2nd}}$ are compared in retry chain 0, $c_{\text{2nd}}$ and $c_{\text{probe}}$ are compared in retry chain 1, and $c_{\text{best}}$ and $c_{\text{probe}}$ are compared in retry chain 2. Then, the future $c_{\text{best}}$ and $c_{\text{2nd}}$ are determined by the results of the three comparisons.

One possible problem with this league match based algorithm is that if $c_{\text{best}}$ is in good channel condition, there is no retransmission for $S_{\text{best}}$, and hence, FSR of $c_{\text{2nd}}$ in retry chain 1 cannot be obtained. As a result, $c_{\text{2nd}}$ cannot be compared with $c_{\text{probe}}$ in retry chain 1 and cannot be updated even though $c_{\text{probe}}$ is better than $c_{\text{2nd}}$. In our Best2Match, thus, $c_{\text{2nd}}$ is updated to $c_{\text{probe}}$ if $c_{\text{2nd}}$ is not used due to the relatively low FSR than $c_{\text{best}}$ and FSR of $c_{\text{probe}}$ in retry chain 1 is equal to 1, i.e., $c_{\text{2nd}}$ is in bad channel condition and $c_{\text{probe}}$ is expected to be in good channel condition (lines 10–17 and 20–21). The detailed algorithm is described in Algorithm 3.

The final version of our transmit antenna selection algorithm, Best2Match, has two benefits compared with Best1Probe and Best2Probe. Best1Probe is a baseline algorithm following the basic procedure in [11], and Best2Probe is an intermediate version. First, Best2Match can reduce the performance degradation due to probing, since it carries out probing only when it is required. Specifically, the probed combination is used for retry chain 1 or 2, which is after all

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8Average channel gain of antenna combination, $c$, is equal to $\sqrt{\sum_i s_i^2 r_i}$.
Algorithm 3 Best2Match

1: Set $T_{\text{interval}}$ \(\triangleright\) set time interval for decision
2: while transmission do
3: \(\triangleright\) initiate FSR of retry chain 0, 1, 2
4: \(\triangleright\) set timer to 0
5: while timer < $T_{\text{interval}}$ do
6: \(\triangleright\) set only 2nd best comb. for retry chain 0
7: Update $P_{\text{best1}}(c_{\text{best1}})$ and $P_{\text{best2}}(c_{\text{best2}})$
8: end while

Algorithm 4 MiDAS

1: Set $T_{\text{window}}$ \(\triangleright\) set time window
2: $K \leftarrow T_{\text{window}}/T_{\text{interval}}$ \(\triangleright\) \# of time intervals
3: for $i \leftarrow 1..K$ do
4: \(\triangleright\) \# of selections of antenna combination $c$ with MCS $m$
5: end for
6: while transmission do
7: \(\triangleright\) track $N_K(c, m)$ during $T_{\text{interval}}$
8: for $j \leftarrow \text{timer}...1$ do
9: Update $N_K(c, m)$
10: end for
11: if $c_{\text{default}} \leftarrow \arg \max \sum_{i=0}^{K-1} \sum_{m=0}^{\text{max}} N_i(c, m)/R(m)$
12: end if
13: for $i \leftarrow 1..K$ do
14: \(\triangleright\) memorization for $T_{\text{window}}$
15: end for
16: end while

It is worth mentioning that the default antenna combination selected by MiDAS could operate well not only for multicast and beacon transmission but also for reception since the throughput of DL and UL are highly correlated as discussed in Section III.

V. PERFORMANCE EVALUATION

To demonstrate the practicality of the proposed antenna selection algorithms, we have implemented the algorithms in Samsung WEA303 AP. By conducting measurements with the AP and five smartphones (Samsung Galaxy S3), we evaluate the performance of the transmit antenna selection algorithms (Best1Probe, Best2Probe, and Best2Match), and default antenna selection algorithm (MiDAS). The measurements are carried out in the office environment shown in Fig. 4, where the stations are placed at five different positions (positions 2–6 in Fig. 4). The AP configuration is the same as in Section III.

A. Performance of Proposed Transmit Antenna Selection

To evaluate the performance of the proposed transmit antenna selection algorithms, we measure the DL UDP throughput for two cases, single station case and multiple station case. In the single station case, only one of the five stations is connected to the AP, where the AP generates DL UDP packets for the station. In the multiple station case, on the other hand, all the five stations are connected to the AP, and the AP generates DL UDP packets for the five stations with equal source rates. In each case, we measure DL throughput during 30 s repeating for 8 fixed antenna combinations, Best1Probe, Best2Probe, and Best2Match. Therefore, one iteration consists of the 11 measurements, and total 10 iterations are carried out for each deployment. As explained in Section III, we make a stationary measurement environment, so channel states are relatively static. The parameters for algorithms are configured as $T_{\text{interval}}=100$ ms, $D_{\text{fsr}}=0.15$, and $T_{\text{window}}=5$ s.

Fig. 6 shows the average throughput for each iteration at the five different positions, and it can be interpreted as a temporal throughput change depending on the antenna selection, i.e., fixed, Best1Probe, Best2Probe, or Best2Match. Each bar of 8 Fixed corresponds to the throughput of a fixed antenna combination.

There are five deployments for the single station case while there are only one deployment for the multiple station case.
In the single station case, there exists a fixed antenna combination which performs the best for each station, and Best2Match is observed to track the best fixed antenna combination properly, while Best1Probe and Best2Probe show performance degradation due to probing even though they track the best antenna combination properly. In the multiple station case, the proposed algorithms are able to achieve higher throughput than the best fixed antenna combination. It is because the best fixed antenna is not the best for each individual station while proposed algorithms can track and use the best antenna combination for each station.

In both cases, we observe the gain of Best2Match obtained by eliminating the unnecessary probing. However, due to the static channel condition, we cannot observed the gain from alternative use of two antenna combinations. Thus, we carry out another measurement in a mobile environment. As shown in Fig. 4, the station labeled ‘M’ moves back and forth following the straight red line (about 2 m long). The motion is controlled by a configurable robot car, HBE-RoboCar [19], whose speed can be configured up to 0.5 m/s. To focus on the moving station, no other station is connected to the AP, while the AP transmits DL UDP packets for the station for 30 s. We measure the downlink UDP throughput with 8 different fixed antenna combinations, Best1Probe, Best2Probe, and Best2Match, for 10 iterations.

Fig. 7 shows the empirical cumulative distribution functions (ECDF) of the measured throughput in the mobile environment with the speeds of 0.3, 0.4, and 0.5 m/s. For all speeds, there is no performance gain from Best1Probe compared with 8 Fixed. On the other hand, Best2Probe and Best2Match achieve significant enhancement by alternatively using two antenna combinations, whereas the enhancement becomes even larger for higher speed.

The measurement results of the transmit antenna selection algorithms in the static and mobile environments are summarized in Table IV. The measured throughput of each iteration is averaged, and 8 fixed antenna combinations are averaged together. The gain of Best2Match compared with the average of 8 fixed antenna combinations is also listed in Table IV. In the static channel case, Best2Match improves the throughput by about 10.0% and 33.8% compared with

<table>
<thead>
<tr>
<th>Static (Mb/s)</th>
<th>8 Fixed</th>
<th>Best1P</th>
<th>Best2P</th>
<th>Best2M</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>24.05</td>
<td>24.51</td>
<td>24.25</td>
<td>26.44</td>
<td>9.95</td>
</tr>
<tr>
<td>Multiple</td>
<td>4.12</td>
<td>5.42</td>
<td>5.36</td>
<td>5.51</td>
<td>33.77</td>
</tr>
<tr>
<td>0.3 m/s</td>
<td>21.08</td>
<td>20.81</td>
<td>20.07</td>
<td>24.15</td>
<td>14.55</td>
</tr>
<tr>
<td>0.5 m/s</td>
<td>18.70</td>
<td>18.94</td>
<td>21.86</td>
<td>22.94</td>
<td>22.66</td>
</tr>
</tbody>
</table>

We conduct the measurement with the moving station at edge region to make the environment where the station experiences bad channel frequently.

![Fig. 6. Temporal throughput change with transmit antenna selection in (a) single station case and (b) multiple station case.](image)

![Fig. 7. Empirical CDF of throughput with the speed of (a) 0.3 m/s, (b) 0.4 m/s, and (c) 0.5 m/s.](image)
the average of 8 fixed antenna combinations for the single station case and for the multiple station case, respectively. In the mobile channel case, Best2Match improves the throughput by about 14.6%, 18.0%, and 22.7% compared with the average of 8 fixed antenna combinations respectively for the speed of 0.3, 0.4, and 0.5 m/s. Due to the limitation of HBE-RoboCar, measurement with the higher speed than 0.5 m/s is not carried out, but the larger enhancement is expected with the typical walking speed over 0.5 m/s. Furthermore, Best2Match is expected to give more performance gain when multiple mobile stations are associated with an AP, which is the typical environment of infrastructure-based WLAN with smartphones.

B. Performance of Proposed Default Antenna Selection

To evaluate the default antenna selection algorithm, MiDAS, we compare the downlink multicast throughput of MiDAS with multicast throughputs of 8 different fixed default antenna cases. The AP generates multicast packets for the five stations with source rate of 5 Mb/s, and generates unicast packets for the five stations with 6 Mb/s source rates. The AP uses Best2Match for the transmit antenna selection, which collaborates with MiDAS. We measure the multicast throughput of each station for 30 s, and 10 iterations are carried out in the static channel without mobility.

Fig. 8 shows temporal throughput and frame error rate (FER) changes of the worst station, which has the lowest throughput among five stations for each iteration. The default antenna is desired to guarantee the performance of all the associated stations including the stations in bad condition. Therefore, the performance of the worst station is an important factor. For the fixed antenna combination, the throughput and FER vary significantly, and the worst station might not be able to receive the multicast packets with certain default antenna combinations. However, MiDAS closely follows the best antenna combination of the worst station, thus achieving the throughput over 4 Mb/s and FER under 0.2.

The measurement results of MiDAS including the throughput and FER of the worst station are summarized in Table V. MiDAS improves the throughput of the worst station by about 23.3% and reduces FER by about 53.6% compared with the average of 8 fixed default antenna combinations.

TABLE V. Summary of default antenna performance.

<table>
<thead>
<tr>
<th>THR (Mb/s)</th>
<th>8 Fixed–average</th>
<th>MiDAS</th>
<th>Gain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.49</td>
<td>4.30</td>
<td>23.29</td>
<td></td>
</tr>
<tr>
<td>0.26</td>
<td>0.12</td>
<td>53.58</td>
<td></td>
</tr>
</tbody>
</table>

VI. CONCLUSION AND FUTURE WORK

We present an antenna selection system for infrastructure-based WLANs, which is applicable to commercial WLAN devices. Practical antenna selection algorithms of AP for unicast/multicast transmission and reception are proposed by considering practical issues. By alternatively using two best antenna combinations and reducing unnecessary probing overhead, the proposed algorithms achieve significant performance gain. The algorithms are evaluated via measurements with prototype implementation in a commercial AP. To the best of our knowledge, we are the first to present antenna selection algorithms without using CSI. We plan to extend our algorithms to incorporate the support of multi-user MIMO in the future.

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