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# Applying Antenna Selection in WLANs for Achieving Broadband Multimedia Communications

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***Abstract*—A combination of orthogonal frequency division multiplexing (OFDM) and Multiple-input-multiple-output (MIMO) systems appears to be a promising solution for the PHY layer of indoor multimedia transmission via wireless Local Area Networks (WLANs). Antenna selection is an excellent way of reducing the hardware costs of MIMO-OFDM systems while retaining high performance. This paper addresses two major practical concerns for the application of antenna selection: antenna selection training protocol design, and calibration to solve RF imbalance. We present novel solutions that are especially suitable for slowly time-varying environments, e.g., indoor scenarios, sports stadiums, and shopping malls. Specifically, a low Doppler spread associated with such environments enables us to train all antenna subsets by multiple training packets transmitted in burst; consequently antenna selection techniques can be accommodated in the emerging standards with minimum modifications. In order to deal with RF imbalance, we propose a novel calibration procedure that reduces the performance degradations. Both numerical and analytical approaches are used to verify the effectiveness of the proposed solutions, which make antenna selection more easily adaptable for high-throughput WLAN systems. Our solutions have been accommodated in the current draft of the IEEE 802.11n standard for high-throughput WLANs.**

***Index Terms*—Antenna selection, MIMO-OFDM, RF imbalance, WLAN.**

## I. INTRODUCTION

THE transmission of high-speed data, e.g. multimedia content, via wireless networks has drawn great attention in recent years. Many of the emerging applications require transmission over relatively short distances, but with very high quality and throughput. For example, wireless multimedia home networks transmit multiple HDTV connections, requiring both high data rates and reliable packet error rate performance. Another example is broadcasting in a sports stadium, where individual visitors might request replays of highlights from different camera views; due to the high user density, large total data rates are required. Wireless Local Area Networks (WLANs) are well suited for such applications, because they offer high throughput, high area spectral efficiency, and low power consumption, over relatively short distances (up to 100 m) [17]. For this reason, all leading consumer-electronics companies have shown great interest in the WLANs, and actively contributed features that enhance multimedia transmission to the WLAN standardization.

WLAN technology has greatly advanced in the past 5 years, and WLANs based on the IEEE 802.11 standard [4], [17] are currently one of the hottest sectors of the wireless market. The current IEEE 802.11a/g standard, which is based on Orthogonal Frequency Division Multiplexing (OFDM), is limited to data rates of 54 Mbit/s. On the other hand, it has been shown that with appropriate channel estimation and frequency/timing synchronizations, the combinations of OFDM with multiple input multiple output (MIMO) techniques is effective in achieving high throughput data communications [5]–[9], [15]. By adopting MIMO-OFDM, the emerging IEEE 802.11n high-throughput WLAN standard targets on data rates in excess of 100 Mbps, as observed at the MAC-layer service access point (SAP) [1].

The remarkable ability of MIMO wireless communication system can be mostly explained by its spatial diversity and spatial multiplexing (SM) gains [3]. A major potential problem for the practical implementation of MIMO systems is their increased hardware cost: every antenna element necessitates a complete RF (up-conversion or down-conversion) chain, including mixers, amplifiers and analogue-to-digital conversion. Another issue with MIMO systems is that high throughput (spatial multiplexing gain) and high reliability (spatial diversity) are competing factors, i.e., cannot simultaneously be obtained to their fullest extent [3], [10].

Antenna subset selection is an attractive solution to the complexity issue, and furthermore greatly improves the throughput/reliability tradeoff ([11], [12] and references therein). In such subset selections, the number of RF chains is smaller than the actual number of antenna elements. The RF chains are connected to the "best" antenna elements, where "best" depends on the channel state (i.e., can vary with time). In many scenarios, judicious antenna selection may incur little or no loss in system performance, while significantly reducing system cost (compared to full-complexity systems with the same number of antenna elements). Moreover, theoretical analysis showed that antenna selection maintains the high data rate of spatial multiplexing MIMO systems, and improves diversity order in each data stream without complex space-time processing at transmitters and receivers [13] (compared to a full-complexity system with the same number of RF chains). The increased diversity order boosts performance especially at high SNR, which is the operating regime of WLANs.

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Color versions of Figs. 3, 4, and 6–8 are available online at http://ieeexplore.ieee.org.

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While the theoretical benefits of antenna selection are firmly established in the literature [11], [13], [14], aspects of practical implementation have not received much attention. Most of the previous discussions in the literature assume that the training for all the antenna elements is done quasi-simultaneously, by subsequently transmitting and receiving multiple repetitions of a training sequence from different antenna elements. This is only possible if the switching times are very fast, which in turn requires that transceivers use solid-state switches, leading to large switching losses [15]. Furthermore, the PHY-layer protocols for such quasi-simultaneous training have to be modified considerably from the non-selection case.

The current paper presents a MAC-based AS training and calibration protocol that eliminates the switching-time problem; furthermore, this scheme requires only minimal modifications compared to a MAC that does not support antenna selection. In our scheme, different antenna subsets are trained in multiple data packets (burst), where each packet contains only a "standard" training packet (identical to a training packet for a non-selection system with the same number of RF chains), plus signaling in the MAC headers. Thus, a minimum overhead increase can be achieved. It will be shown that switching antenna subsets between packets does not significantly reduce the performances, thanks to the low Doppler spread of indoor WLAN channels.

Another important issue of implementing AS, which is largely ignored previously in the literature, is the RF imbalance caused by antenna switching. Different combinations of RF chains and antenna elements may induce non-identical channel gains in the equivalent baseband channels. Thus, an antenna that might have been found to be optimum during training (connecting it to a certain RF chain) might not be optimum for data transmission (using a different RF chain). We solve this RF imbalance problem by proposing a novel over-the-air calibration procedure.

The rest of this paper is organized as follows. In Section II, we give the system model, followed by the introduction of the MAC-based WLAN AS training protocol in Section III. Section IV provides the solutions used for addressing AS with RF imbalance; and numerical results are present in Section V; finally Section VI concludes this paper.

## II. System Models

In the MIMO-OFDM system applying AS (Fig. 1), the transmit station A (STA A) has a set of $N_A$ antennas with $n_A \leq N_A$ transmit RF chains, while $N_B$ and $n_B$ are similarly defined at the receive station B. Antenna switches are applied so that the optimal subset of antennas are selected and connected to the RF chains, based on current channel state information (CSI). In general each AS training cycle consists of an *AS training phase* and a *data transmission phase* (Fig. 2). Several *AS training fields* are transmitted in each AS training phase, each of them is transmitted from and/or received by one subset of available antenna elements. The period of one AS cycle (training plus data transmission) is denoted as $T_{AS}$ (Fig. 2). The computation of the best antennas is based on the channel state information between all $N_A$ transmit and all $N_B$ receive antenna elements, on all OFDM subcarriers. This channel state information is estimated from all the AS training fields

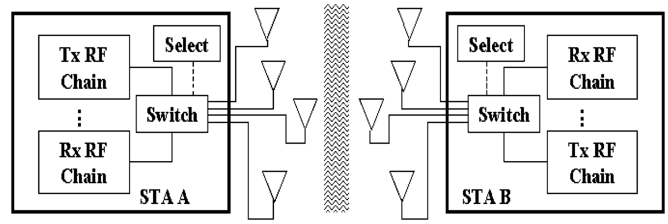


Fig. 1. Antenna selection system model.

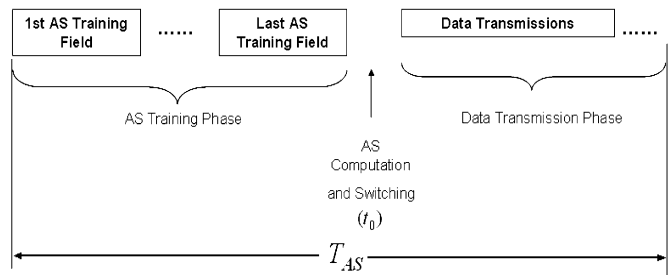


Fig. 2. Antenna selection training and data transmission phases.

within one training cycle. In the data transmission phase, a relationship between a transmitted signal and a received signal in each OFDM subcarrier (for denotation simplicity we omit the subcarrier index here) can be expressed as:

$$\mathbf{r}_B = \mathbf{F}_B^H \left[ \tilde{\mathbf{H}}_{AB}(t)\mathbf{F}_A\mathbf{s}_A + \mathbf{n} \right], \tag{1}$$

where $\mathbf{r}_B$ is a $n_B \times 1$ received signal vector, $\mathbf{s}_A$ is a $n_A \times 1$ transmitted signal vector, and $\tilde{\mathbf{H}}_{AB}(t)$ is a $N_B \times N_A$ *equivalent-baseband time-varying channel matrix containing the complete physical channel responses and the effect of the antennas as well as the impulse responses of the transmit and receive RF chains*, where $t$ represents the time. A noise vector $\mathbf{n}$ has $N_B \times 1$ entries that are independent and identically distributed (i.i.d.) zero-mean circular complex Gaussian random variables with variance $N_0$. $\mathbf{F}_A$ is a $N_A \times n_A$ transmit antenna selection matrix, and $\mathbf{F}_B$ is a $N_B \times n_B$ receive antenna selection matrix. Both $\mathbf{F}_A$ and $\mathbf{F}_B$ are submatrices of an identity matrix, representing antenna selection. The equivalent channel matrix after antenna selection is a $n_B \times n_A$ matrix $\mathbf{H}_{SL} = \mathbf{F}_B^H \tilde{\mathbf{H}}_{AB}(t)\mathbf{F}_A$, which is a *submatrix* of the *complete channel matrix* $\tilde{\mathbf{H}}_{AB}(t)$. The superscript '$H$' denotes the conjugate transpose. As mentioned earlier, the equivalent channel $\tilde{\mathbf{H}}_{AB}(t)$ also includes the impact of the RF responses:

$$\tilde{\mathbf{H}}_{AB}(t) = \mathbf{C}_{B,Rx}(\mathbf{F}_B)\mathbf{H}_{AB}(t)\mathbf{C}_{A,Tx}(\mathbf{F}_A), \tag{2}$$

where $\mathbf{H}_{AB}(t)$ is the physical propagation channel, $\mathbf{C}_{A,Tx}(\mathbf{F}_A)$ is a $N_A \times N_A$ diagonal matrix whose *i-th* diagonal element $[\mathbf{C}_{A,Tx}(\mathbf{F}_A)]_{ii}$ describes the RF response corresponding to the *i-th* transmit antenna element, which is a function of the antenna selection matrix $\mathbf{F}_A$: if the *i-th* row in $\mathbf{F}_A$ contains all zeros, the *i-th* antenna is not selected, so $[\mathbf{C}_{A,Tx}(\mathbf{F}_A)]_{ii} = 0$; if the element at the *i-th* row and *l-th* column of $\mathbf{F}_A$ is one, the *i-th* antenna is selected and is connected to the *l-th* transmit RF chain during the data transmission phase. Then $[\mathbf{C}_{A,Tx}(\mathbf{F}_A)]_{ii} = \alpha_{li}^{(Tx)}$, which is a complex number characterizing both the amplitude attenuation and phase shift of the RF response (seen at baseband) corresponding to the connection between transmit RF chain $l$ and antenna element $i$. $\mathbf{C}_{B,Rx}(\mathbf{F}_B)$ is similarly defined: $[\mathbf{C}_{B,Rx}(\mathbf{F}_B)]_{jj} = \beta_{li}^{(Rx)}$ if the element at the *j-th* row and *l-th* column of $\mathbf{F}_B$ is one. Here $\mathbf{C}_{A,Tx}(\mathbf{F}_A)$ and $\mathbf{C}_{B,Rx}(\mathbf{F}_B)$ are diagonal, since we assume perfect separations among different RF chains. In reality, a 30–40 dB of cross-talk mitigation is achievable, so the off-diagonal entries in $\mathbf{C}_{A,Tx}(\mathbf{F}_A)$ and $\mathbf{C}_{B,Rx}(\mathbf{F}_B)$ can be approximately assumed to be zero.

On the other hand, in the *m-th* AS training field, a relationship between a transmitted signal and a received signal can be expressed as:

$$\mathbf{r}_{B\_T}(m) = \mathbf{T}_B^H(m)\left[\tilde{\mathbf{H}}_{AB}(t_m)\mathbf{T}_A(m)\mathbf{s}_{A\_T} + \mathbf{n}\right], \tag{3}$$

where $t_m$ is the time at which the $m$-th training field is received, $\mathbf{s}_{A\_T}$ and $\mathbf{r}_{B\_T}$ are the training and received vectors; $\mathbf{T}_A(m)$ and $\mathbf{T}_B(m)$ are the predetermined antenna mapping matrices in the $m$-th AS training field, indicating the (pre-determined) connections of all the available RF chains to the $m$-th antenna subset. All these antenna subsets are typically mutually exclusive. For example, if $N_A = 4$, $n_A = 2$, $N_B = 2$, $n_B = 2$, in the case of disjoint antenna subset training, we have 2 training fields with the transmit antenna mapping matrices:

$$\mathbf{T}_A(1) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \quad \text{and} \quad \mathbf{T}_A(2) = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

Then there are totally $M = \lceil N_A/n_A \rceil \lceil N_B/n_B \rceil$ training fields, where $\lceil x \rceil$ is the smallest integer larger than or equal to $x$. STA B can estimate the complete channel matrix (which will be used for AS computations) by combining the $M$ training fields.

The time-variation in $\mathbf{H}_{AB}(t)$ (cf. (2)) is a key factor for designing AS training protocols. It has to be assured that the training and subsequent data transmission occurs within a time that is (much) shorter than the coherence time of the channel. Formulating this mathematically, we denote $t_0$ as the time when AS computation is conducted (see Fig. 2); then the channel estimation used for AS computation is heavily distorted if $\mathbf{H}_{AB}(t)$ varies significantly within $|t_0 - t_m|\ \exists m \in [1, M]$; similarly, during the data transmission phase ($t \geq t_0$), the previously selection result gets stale if $\mathbf{H}_{AB}(t)$ varies significantly within $|t - t_0|$.

To illustrate different kinds of distortions imposed on AS channel estimations, we investigate an exact expression for the complete channel matrix: by ignoring channel estimation errors, the estimated subchannel by training field $m$ is

$$\begin{aligned}\tilde{\mathbf{H}}'_{AB}(m) = \mathbf{T}_B^H(m)\mathbf{C}_{B,Rx}\left(\mathbf{T}_B(m)\right)\mathbf{H}_{AB}(t_m)&. \\ \mathbf{C}_{A,Tx}\left(\mathbf{T}_A(m)\right)\mathbf{T}_A(m)&, \end{aligned} \tag{4}$$

so the AS computation is conducted based on the following estimated complete channel matrix:

$$\tilde{\mathbf{H}}'_{AB} = \mathbf{C}'_{B,Rx}\mathbf{H}_{AB}^{\text{comb}}\mathbf{C}'_{A,Tx}, \tag{5}$$

where the diagonal matrix $\mathbf{C}'_{A,Tx}$ contains all non-zero diagonal values: $[\mathbf{C}'_{A,Tx}]_{ii} = [\mathbf{C}_{A,Tx}(\mathbf{T}_A(m))]_{ii}$, if the *i-th* antenna element is trained by the $m$*-th* training field, and $\mathbf{C}'_{B,Rx}$ is similarly defined; $\mathbf{H}_{AB}^{\text{comb}}$ is a composite physical channel matrix, in which the *k-th* column/row is equal to $[\mathbf{H}_{AB}(t_m)]_{*k}$ or $[\mathbf{H}_{AB}(t_m)]_{k*}$ if it is trained in the $m$*-th* training field. AS computation is based on the estimated complete matrix $\tilde{\mathbf{H}}'_{AB}$ in (5). When using a selection criterion $X(\mathbf{A})$, the selection can be expressed as:

$$\{\mathbf{F}_{A,opt}, \mathbf{F}_{B,opt}\} = \arg\max_{\mathbf{F}_A,\mathbf{F}_B} X\left(\mathbf{F}_B^H\tilde{\mathbf{H}}'_{AB}\mathbf{F}_A\right). \tag{6}$$

For example, if the criterion is the maximization of the capacity, we have [5]

$$X(\mathbf{A}) = \log_2\left|\mathbf{I} + (\rho_0/n_A)\mathbf{A}\mathbf{A}^H\right|, \tag{7}$$

where $\rho_0$ is the average received signal-to-noise ratio.

The inaccuracy in the physical channel due to time variation can be expressed by:

$$\mathbf{H}_{AB}^{\text{comb}} = \mathbf{H}_{AB}(t_0) + \Delta\mathbf{H}_{AB}, \tag{8}$$

which may distort $\tilde{\mathbf{H}}'_{AB}$ in (5), and is named *additive distortion*. Secondly, there can be errors due to the fact that the impulse responses of the RF chains can be different in the training- and the data reception phases. Assume that the physical channel is time-invariant (i.e. $\mathbf{H}_{AB}(t_0) = \mathbf{H}_{AB}(t) = \mathbf{H}_{AB}, \forall\ t$). Let $\mathbf{F}_{A,opt}$, $\mathbf{F}_{B,opt}$ in (6) be selected based on the training phase. The equivalent channel in the data transmission phase becomes

$$\mathbf{H}_{SL} = \mathbf{F}_{B,opt}^H\mathbf{C}_{B,Rx}(\mathbf{F}_{B,opt})\mathbf{H}_{AB}\mathbf{C}_{A,Tx}(\mathbf{F}_{A,opt})\mathbf{F}_{A,opt}. \tag{9}$$

Then $X(\mathbf{H}_{SL})$ may not be optimal, because the RF responses of the used RF chains are different in the two phases. This effect is called *RF imbalance* or *productive distortion*.

In the example of $N_A = 4$, $n_A = 2$, $N_B = 2$, $n_B = 2$ (i.e. only STA A conducts AS), the selection is determined by

$$\tilde{\mathbf{H}}'_{AB} = \mathbf{C}_B^{(Rx)}\mathbf{H}_{AB}\begin{bmatrix} \alpha_{11}^{(Tx)} & & & \\ & \alpha_{22}^{(Tx)} & & \\ & & \alpha_{13}^{(Tx)} & \\ & & & \alpha_{24}^{(Tx)} \end{bmatrix}. \tag{10}$$

where $\mathbf{C}_B^{(Rx)}$ is always fixed given $\mathbf{F}_B = \mathbf{T}_B = \mathbf{I}$. If antennas 1 and 3 are selected at STA A, there will be a distortion of the channel matrix during data transmission phase,

$$\tilde{\mathbf{H}}_{AB} = \mathbf{C}_B^{(Rx)}\mathbf{H}_{AB}\begin{bmatrix} \alpha_{11}^{(Tx)} & & & \\ & 0 & & \\ & & \alpha_{23}^{(Tx)} & \\ & & & 0 \end{bmatrix}, \tag{11}$$

if $\alpha_{13}^{(Tx)} \neq \alpha_{23}^{(Tx)}$, and therefore transmit antennas 1 and 3 may not be the optimal subset.

For simplicity and without loss of generality, we henceforth use the following constraint: for any selected antenna subset, a RF chain with smaller index number always connects to an

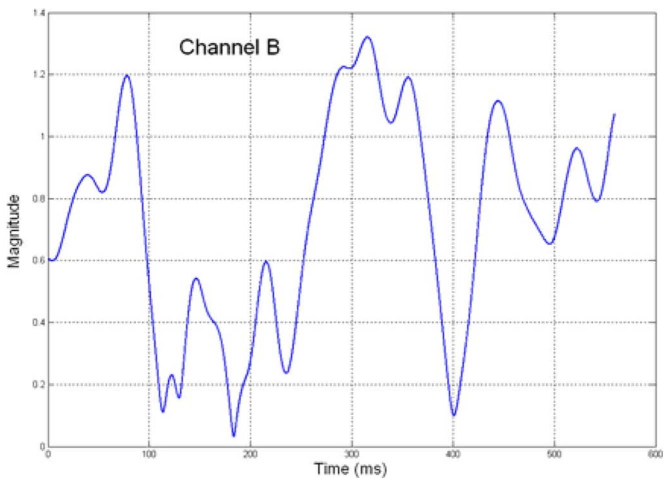


Fig. 3. Example time variation in channel model B.

antenna with smaller index. With this constraint, in both the AS training phase and the data transmission phase there are totally $n_A \times (N_A - n_A + 1)$ possible connections of an RF chain with an antenna element at STA A, and all the possible RF responses can be expressed as:

$$\mathbf{A}^{(Tx)} = \begin{bmatrix} a_{11}^{(Tx)} & a_{22}^{(Tx)} & \cdots & a_{n_A n_A}^{(Tx)} \\ a_{12}^{(Tx)} & a_{23}^{(Tx)} & \cdots & a_{n_A (n_A+1)}^{(Tx)} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1(N_A - n_A + 1)}^{(Tx)} & a_{2(N_A - n_A + 2)}^{(Tx)} & \cdots & a_{n_A N_A}^{(Tx)} \end{bmatrix}. \tag{12}$$

Similarly, the same constraint is also applied to the receiving station.

In the following two sections, we address the additive and productive distortions by proposing an effective MAC-based AS training protocol, as well as a simple calibration algorithm.

## III. Antenna Selection Training Protocol in High-Throughput WLAN

Indoor WLAN channels assume Doppler spreads as low as 5 Hz, corresponding to a coherence time of hundreds of milliseconds (see Fig. 3 for a WLAN channel realization [2]). This implies $\mathbf{H}_{AB}(t_m) \approx \mathbf{H}_{AB}(t_0)$, if all the AS training fields are transmitted within a relatively short interval. Therefore we have $\mathbf{H}_{AB}^{\text{comb}} \approx \mathbf{H}_{AB}(t_0)$ (cf. (5)), and the additive distortion can be minimized.

As mentioned earlier, the AS training method that extends the PHY layer preamble, although optimal for minimizing additive distortions, induces difficulties for the antenna switch designs. On the other hand, we have seen above that for our applications the training fields can be distributed over a longer period of time, since in indoor channels $\mathbf{H}_{AB}(t) \approx \mathbf{H}_{AB}(t_0)$, $t \in [t_0, T_{AS}]$ over large values of $T_{AS}$ (cf. Fig. 2). We thus propose a MAC-based AS training protocol, where the AS training phase is formed by a sequence of $M$ consecutive training packets. Each packet contains one of $M$ AS training fields, which is transmitted from and/or received by one of the $M$ disjoint antenna subsets. Note that these training fields are identical to training fields of conventional MIMO systems with dimension $n_B \times n_A$. Additional signaling information (e.g., the number of training fields) is transmitted in the MAC headers.[1] Therefore the proposed training method greatly reduces the required modifications in the standard.

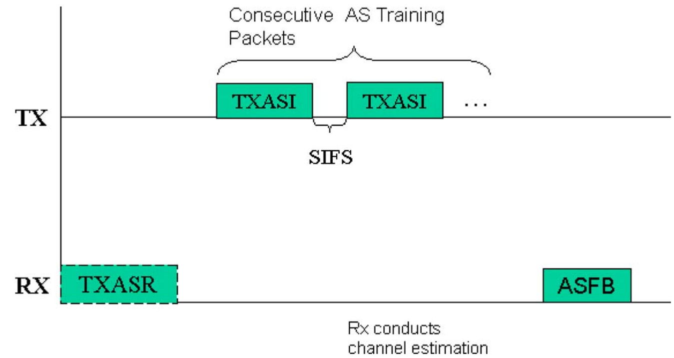


Fig. 4. Transmit AS training example.

In order to keep the duration of the training process as short as possible (so $\mathbf{H}_{AB}^{\text{comb}} \approx \mathbf{H}_{AB}(t_0)$), the training packets should be sent one shortly after the other in a burst to maintain a short duration of AS training phase. This is illustrated in Fig. 4, using an example of transmit AS training only. This protocol can be described as follows:

1) The receiver may choose to initiate the AS training cycle by sending a transmit AS request (TXASR), whenever the current selection result gets stale. Or the transmitter can initiate its own AS training cycle at a predetermined time, or when it observes more frequent re-transmissions of packets.
2) Then the transmitter sends out $M = \lceil N_A / n_A \rceil$ consecutive AS training packets separated (in the 802.11 standard) by short inter-frame interval (SIFS, equal to 16 $\mu$s [1]). Each packet contains the regular long and short OFDM training fields in its preamble as defined in [1], and is transmitted from one subset of $n_A$ antennas. The time available for switching the antennas is now one SIFS, allowing to implement the Micro Electro Mechanical Systems (MEMS) based switches, which have much lower switching attenuation than solid-state switches [16].
3) On receiving these packets, the receiver conducts channel estimations to establish the complete channel matrix for each subcarrier.
4) Finally the receiver may either compute the "best" antennas and feed back the selected antenna indices, or directly feed back the complete channel matrices for the transmitter, which then conducts the selection.

The receiver AS training process can be similarly defined, except that now different AS training packets are received by different receive antenna subsets. When both sides conduct antenna selection, the two training processes can be done one after another, or the complete channel matrix can be established, and a joint selection (best TX and best RX antennas) can be performed.

[1]A dedicated high-throughput control field is already defined for signaling the new MIMO high-throughput features such as transmit beam forming and fast link adaptations [1].

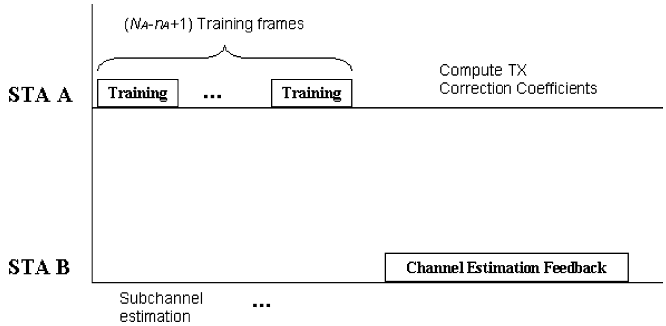


Fig. 5. Transmit AS calibration process.

## IV. AS With RF Imbalance

To recover the possible performance degradation caused by the productive distortion or RF imbalance, one feasible solution is to train each *possible* antenna subset during *each* of the AS training phases. However, this obviously is impractical for large numbers of antenna elements and/or RF chains, and may induce more additive distortions since the AS training phase becomes longer.

Instead, we propose to mitigate multiplicative distortions by a simple calibration process. Since the RF responses vary with the environment (e.g., temperature variations), an over-the-air calibration process is necessary. On the other hand, the overhead for calibration is negligible because it needs to be conducted only at large time intervals, e.g., only upon station association, or when the environment varies.

Fig. 5 shows the calibration procedure for transmit AS.

1) The transmitter (STA A) sends consecutively $N_A - n_A + 1$ AS calibration training packets, each transmitted with the RF chain/antenna connections according to one single row of (12). For example, the first training packet uses the connections:

$$\text{RF } 1 \rightarrow \text{Ant } 1, \text{RF } 2 \rightarrow \text{Ant } 2, \ldots, \text{RF } n_A \rightarrow \text{Ant } n_A.$$

2) On receiving these training packets, the receiver (STA B) estimates the corresponding subchannels, denoted as $\tilde{\mathbf{H}}'_{AB}(1) \ldots \tilde{\mathbf{H}}'_{AB}(N_A - n_A + 1)$, and feeds them back after receiving all the training packets.
3) The transmitter then determines its RF imbalance correction coefficients based on all the estimated subchannel matrices fed back from STA B.

When STA B also conducts receive AS, i.e. $N_B > n_B$, it should use a predetermined subset of receive antennas, each connected to a predetermined receive RF chain on receiving all the training packets in Fig. 5.

The correction coefficients are determined as follows: since the low Doppler property in WLAN channel enables us to assume $\mathbf{H}_{AB}^{\text{comb}} \approx \mathbf{H}_{AB}(t_0) \approx \mathbf{H}_{AB}$ (ignoring channel estimation errors), the effective channel transfer function becomes

$$\tilde{\mathbf{H}}'_{AB}(1) = \begin{bmatrix} \tilde{h}_{AB,11}^{(11)} & \tilde{h}_{AB,12}^{(22)} & \cdots & \tilde{h}_{AB,1n_A}^{(n_A n_A)} \\ \tilde{h}_{AB,21}^{(11)} & \tilde{h}_{AB,22}^{(22)} & \cdots & \tilde{h}_{AB,2n_A}^{(n_A n_A)} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{h}_{AB,n_B 1}^{(11)} & \tilde{h}_{AB,n_B 2}^{(22)} & \cdots & \tilde{h}_{AB,n_B n_A}^{(n_A n_A)} \end{bmatrix}, \quad (13)$$

where $\tilde{h}_{AB,j_B i}^{(li)} = \beta_{l_B j_B}^{(Rx)} h_{AB,j_B i} \alpha_{li}^{(Tx)}$ stands for the equivalent channel coefficient involving all the RF responses; $h_{AB,j_B i}$ is the actual physical channel coefficient in $\mathbf{H}_{AB}$ from transmit antenna $i$ to receive antenna $j_B$, which is connected to the predetermined receive RF chain $l_B$, with $\beta_{l_B j_B}^{(Rx)}$ the corresponding receive RF response. $\tilde{\mathbf{H}}'_{AB}(2), \tilde{\mathbf{H}}'_{AB}(3) \ldots \tilde{\mathbf{H}}'_{AB}(N_A - n_A + 1)$ can be expressed similarly based on different transmit RF chain and antenna element connections following the corresponding rows in $\mathbf{A}^{(Tx)}$ in (12). For the $i$-th transmit antenna, we then do the following calculation:

$$\kappa_{li} = \frac{\tilde{h}_{AB,n_B i}^{(\min\{L_i\} i)}}{\tilde{h}_{AB,n_B i}^{(li)}} = \frac{\beta_{l_B j_B}^{(Rx)} h_{AB,j_B i} \alpha_{\min\{L_i\} i}^{(Tx)}}{\beta_{l_B j_B}^{(Rx)} h_{AB,j_B i} \alpha_{li}^{(Tx)}} = \frac{\alpha_{\min\{L_i\} i}^{(Tx)}}{\alpha_{li}^{(Tx)}}, \quad (14)$$

for every $l \in L_i$, where $L_i$ is the set of RF chain indices that are possible to be connected to antenna $i$ according to (12), and $\min\{L_i\}$ is the minimum index in $L_i$. To enforce all signals transmitted from the $i$-th antenna to behave exactly like if they were transmitted from the $\min\{L_i\}$-th RF chain, $\kappa_{li}$ is multiplied with the baseband signal transmitted from any RF chain $l$, whenever it is connected to antenna $i$. As a result, any transmission from antenna $i$ leads to a corresponding transmit RF response $\alpha_{\min\{L_i\} i}^{(Tx)}$. As special cases, if transmit antenna 1 $(N_A)$ is selected, then it is always connected to RF chain 1 $(n_A)$, respectively. This follows from the constraint in (12). Thus no correction is needed for the transmissions from them. By doing the same calculations and by applying the results for all transmit antennas, at any time the equivalent complete channel matrix (cf. (2)) can be expressed as:

$$\tilde{\mathbf{H}}_{AB} = \mathbf{C}_{B,Rx} \mathbf{H}_{AB} \cdot diag\left\{ \alpha_{11}^{(Tx)}, \alpha_{12}^{(Tx)}, \cdots, \cdot \alpha_{\min\{L_i\} i}^{(Tx)}, \cdots, \alpha_{n_A N_A}^{(Tx)} \right\}. \quad (15)$$

Then there is no productive distortion between the AS training phase and the data transmission phase. Note that these correction coefficients are applied in both the AS training phase and the data transmission phase, which is equivalent to replacing the 1's in $\mathbf{F}_A$ or $\mathbf{T}_A(m)$ by the corresponding correction coefficients $\{\kappa_{li}\}$. The above calculations can be repeated $n_B$ times, corresponding to $j_B = 1 \cdots n_B$ respectively. The resultant $n_B$ sets of correction coefficients can then be averaged to reduce the impact from channel estimation errors.

The receiver AS calibration process can be similarly defined, where the transmitter should send $(N_B - n_B + 1)$ calibration training packets from a fixed subset of antennas with fixed RF connections. Then the calculation of receive AS correction coefficients is straightforward, as long as we have a similar constraint of receive RF chain and antenna connections as in (12). When both stations perform antenna selections, their calibrations can be conducted one after the other. As a result, the equivalent complete channel matrix always contains fixed transmit and receive RF responses, and the AS training protocol in Section III can be deployed without distortions.

Note that the above calibrations should be conducted for each subcarrier when applied in OFDM systems. Also, they can be straightforwardly applied when the connection constraints in (12) does not hold (i.e. $L_i$ contains any RF chains for any antenna $i$).

Finally, in 802.11n WLAN the calibration frame exchange sequence in Fig. 5 can be conducted by utilizing an ordinary AS training protocol as in Fig. 4, where the receiver should feedback the estimated complete CSI only. In this case, the calibration process is transparent to the peer station, which does not know if the current AS training burst is used for normal AS computation or calibration. Consequently no extra signaling needs to be defined for calibrations.

## V. Numerical Results

In this section, we present simulation results for the performance impact of our training and calibration schemes. All simulations are based on (simplified) IEEE 802.11n systems. We use 64-QAM and rate 3/4 convolution channel coding (rate 1/2 convolution code with puncturing [1]) as the modulation and coding set in each of the two transmitted data streams, with 20 MHz bandwidth and a 0.8 $\mu$s guard interval in each OFDM symbol. Therefore the burst data rate observed at the PHY layer is 117 Mbps. We also assume the simplest least-square channel estimation in each subcarrier, and assume that there is no further impairment from time synchronization errors and RF imperfections such as carrier and sampling frequency offsets, phase noise, I/Q and DC imbalance, AGC/ADC related issues, and transmitter distortions. For each SNR we simulate 10000 packets, each containing 1000 bytes of data payload plus the preamble as defined in [1]. Since the channel encoding and interleaving are conducted over all spatial data streams and all sub-carriers, it is natural to deploy the antenna selection rule which maximizes the aggregated $2 \times 2$ MIMO channel capacity over all subcarriers. We stress that many other effective AS rules have been developed in literature to achieve different tradeoffs between performance gain and sensitivity to $T_{AS}$, and the problem of finding these AS rules, a topic beyond the scope of this paper, can be found in [11], [14] and references therein.

### A. WLAN Channels Without RF Imbalance

In the first scenario where $N_A = 4$, $n_A = 2$, $N_B = 2$, $n_B = 2$, we investigate the effectiveness of the MAC-based AS training method assuming that RF imbalance has no significant impact (i.e. unit RF responses on both devices). The inter-packet interval is set to be 1 ms during the data transmission phase, so that the 10000 packets may experience sufficient channel variations. We show results for training times $T_{AS}$ (as defined in Fig. 2) equal to 10 and 100 ms. For comparison we also simulate the AS training method where all of the $M = 2$ training fields are sent in one packet by extending its PHY preamble and ignoring the switching loss (we call this scheme as "PHY-based" in the figures). From the packet error rate (PER) results in channel model B (Fig. 6), where the channel is under relatively low level of frequency selectivity [2], we see that the proposed MAC-based AS training method leads to almost the same results as PHY-based training method. It is also noticeable that in reality the MAC-based method will even outperform the PHY-based one by a few dB's, when considering the reduced

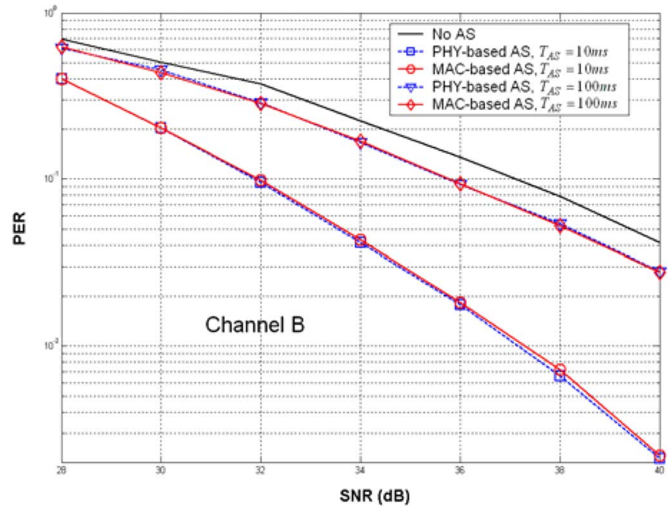


Fig. 6. Results of channel B.

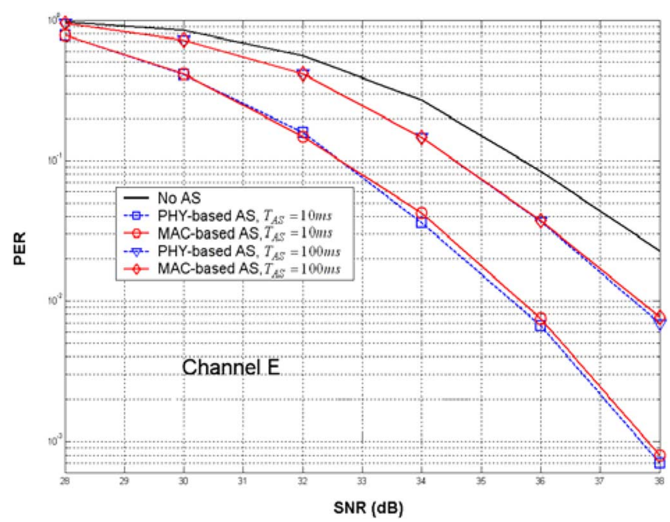


Fig. 7. Results of channel E.

switching loss by introducing MEMS-based antenna switches. From the same figure, we also see that the gains of applying AS in WLAN are tremendous (5 dB when $T_{AS} = 10$ ms, and more than 1 dB when $T_{AS} = 100$ ms).

In channel model E (Fig. 7), where the channel is much more frequency selective [2], the relative gains of AS is reduced (although they are still as high as 3 dB for $T_{AS} = 10$ ms), because the less correlated sub-carriers make different antenna subsets look more "even" with respect to the performance criterion (aggregated capacity or PER).

### B. Calibration for RF Imbalance

In the second scenario, RF imbalance is taken into considerations in channel B, where the PER of a 2-data stream WLAN system without AS, and MAC-based AS with and without calibration (both setting $T_{AS} = 10$ ms), are simulated. Each RF chain and antenna element connection results in a baseband equivalent RF response $\alpha_{li}^{(Tx)}$ with its magnitude uniformly distributed in $\pm 3$ dB, and phase uniformly distributed in $\pm\pi$. We

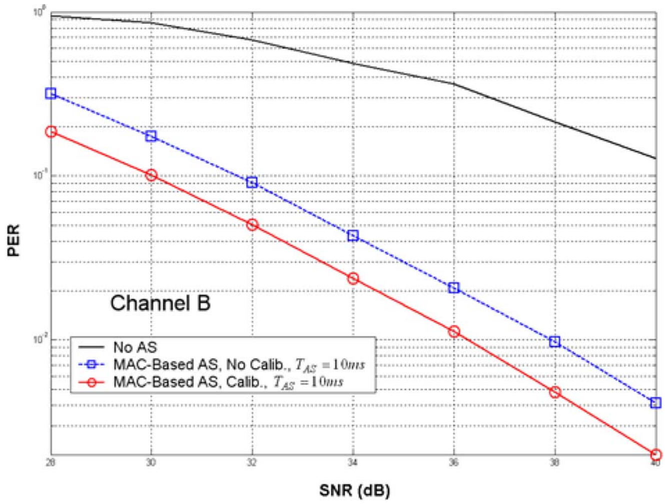


Fig. 8. Results of channel B under RF imbalance.

can then see from Fig. 8 that calibration alleviates the impairment caused by RF imbalance. Hence the proposed AS calibration method, a process imposing negligible training overhead, will buy us about 2 dB gain in this scenario. It is also noteworthy that random RF responses will degrade the performance of $2 \times 2$ MIMO without AS, hence the gains achieved by applying AS is even larger than in Fig. 6.

Note that the achieved high data rate, as well as relatively low PER, make AS suitable for multimedia applications.

## VI. Conclusion

This paper addresses two important issues for employing antenna selection techniques in high throughput WLAN systems for indoor multimedia communications: AS training protocol and mitigation of impairments caused by RF imbalance. The proposed MAC-based AS training method minimizes the amount of modifications required for accommodating AS in a MIMO standard, and leads to several other advantages such as ability to use switches with reduced switching loss. The novel calibration process effectively alleviates the potential impairments caused by RF imbalance, with negligible overhead. In general, the proposed techniques move a step closer to the practical implementation of MIMO antenna selection techniques in high throughput WLAN systems, especially for indoor multimedia applications. They have thus been adopted in the preliminary version of the IEEE 802.11n baseline draft [1].

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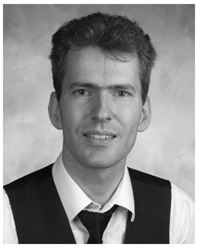

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