Antenna Selection in High-Throughput Wireless LAN

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This paper presents a new method for implementing antenna selection in high-throughput wireless LANs (WLANs), addressing two major practical concerns: antenna selection training protocol design, and calibration to solve RF imbalance problems. Specifically, the low Doppler spread of WLAN channels 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. The proposed solutions in this paper thus make antenna selection more easily adoptable for high-throughput WLAN systems.

I. Introduction

WLANs based on the IEEE 802.11 standard [9], [4], currently are one of the hottest sectors of the wireless market. While the current IEEE 802.11a standard, which is based on Orthogonal Frequency Division Multiplexing (OFDM) is limited to data rates of 54 Mbit/s , the emerging IEEE 802.11n high-throughput WLAN standard combines OFDM with multiple-input-multiple-output (MIMO) techniques to achieve effective data rate in excess of 100Mbps, as observed at 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][4].

The modem design of 802.11n employs closed-loop schemes, which require channel-state information (CSI) at the transmitter. Since the channels in WLANs exhibit slow time variations (low Doppler spread around 5Hz [2]), the transmitter CSI, obtained by feedback or channel estimation in the reverse link, does not get stale at the instance of transmission, making it well suited for implementing closed-loop MIMO algorithms. One good example is transmit beamforming with fast link adaptation techniques as foreseen in the current standard draft [1]. Another example for closed-loop MIMO is transmit antenna selection (AS), which is the focus of this paper.

A major potential problem for the practical implementation of MIMO systems is their increased chip area and hardware cost due to multiple analog/RF front-ends. This has motivated the investigation of antenna selection techniques for MIMO systems [5], because judiciously selecting from a large quantity of inexpensive antenna elements and connecting them to a limited number of RF chains provides substantial diversity gain, while significantly reducing system cost [5][6]. Antenna selection is particularly beneficial for WLANs for the following reasons: 1. the obtained diversity gain may significantly boost the performance especially at high SNR, i.e., the SNRs that are typical for WLANs 2. the slowness of the variations of WLAN channels greatly reduces the overhead required for antenna selection training.

A potential problem of antenna selection is the increased hardware effort that is required by the antenna selection training. If all possible antennas are trained at the beginning of each packet, fast solid-state switches, and fast automatic gain controls (AGCs) are required, leading to large switching loss [7]; furthermore, the PHY-layer protocols have to modified considerably from the non-selection case.

In this paper, we introduce a MAC-based AS training protocol that eliminates all of these problems. In our scheme, different antenna subsets are trained in multiple data packets (burst), and signaled only in the MAC headers. Numerical results show that switching antenna subsets between packets does not significantly reduce the performances, thanks to the low Doppler spread of WLAN channels.

Another important issue of implementing AS, largely ignored previously in the literature, is the RF imbalance caused by antenna switching, because essentially different combinations of RF chains and antenna elements may induce non-identical channel gains in the equivalent baseband channels. We address this problem by proposing a novel calibration procedure.

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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.

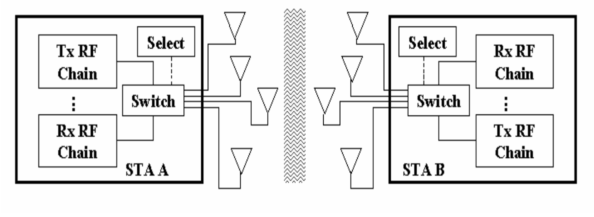

Figure 1. Antenna Selection System Model.

II. System Model and AS Training in WLAN

In the MIMO-OFDM system applying AS (Figure 1), the transmit station A (STA A) has a set of N_A antennas with n_A transmit RF chains, while N_B and n_B are similarly defined at the receive station B. In general each AS training cycle consists of an *AS training phase* and a *data transmission phase*. Several *AS training fields* are transmitted in each AS training phase, each of them is transmitted from and/or received by one subset of antenna elements to be selected. The antenna selection computation is based on the complete channel matrix composed of the subchannels estimated from all the AS training fields. In the data transmission phase, a relationship between a transmitted signal and a received signal in one subcarrier (for denotation simplicity we omit the subcarrier index here) can be expressed as:

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

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 $\tilde{\mathbf{H}}_{AB}$ is a $N_B \times N_A$ *equivalent channel matrix containing complete physical channel responses and the effect of transmit and receive RF responses*. A noise vector **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 $\mathbf{H}_{eq} = \mathbf{F}_B^H\tilde{\mathbf{H}}_{AB}\mathbf{F}_A$, which is a *submatrix* of the *channel matrix* $\tilde{\mathbf{H}}_{AB}$. The superscript '*H*' means the conjugate transpose. The equivalent channel $\tilde{\mathbf{H}}_{AB}$ also includes the impact of the RF responses:

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

where $\mathbf{H}_{AB}$ is the actual propagation channel, $\mathbf{C}_{A,Tx}(\mathbf{F}_A)$ is a $N_A \times N_A$ diagonal matrix whose *i-th* diagonal element $[\mathbf{C}_{A,Tx}(\mathbf{F}_A)]_{ii}$ collects 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 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.

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:

$$\mathbf{r}_{B,t}(m) = \mathbf{T}_B^H(m)[\tilde{\mathbf{H}}_{AB}\mathbf{T}_A(m)\mathbf{s}_{A,t} + \mathbf{n}], \qquad (3)$$

where $\mathbf{s}_{A,t}$ 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 connections of all the available RF chains to the *m-th* antenna subset. All these antenna subsets are typically exclusive with each other. For example, if $N_A = 4, n_A = 2, N_B = 2, n_B = 2$, we have 2 training fields with the transmit antenna mapping matrices:

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

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 then can estimate the complete channel matrix (which will be used for AS computations) by combining the *M* subchannels. Consequently, by ignoring channel estimation errors, the estimated subchannel by training field *m* is

$$\tilde{\mathbf{H}}'_{AB}(m) = \mathbf{T}_B^H(m)\mathbf{C}_{B,Rx}(\mathbf{T}_B(m))\mathbf{H}_{AB}\mathbf{C}_{A,Tx}(\mathbf{T}_A(m))\mathbf{T}_A(m), \qquad (4)$$

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

$$\tilde{\mathbf{H}}'_{AB} = \mathbf{C}'_{B,Rx}\mathbf{H}_{AB}\mathbf{C}'_{A,Tx}\,, \qquad (5)$$

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. Therefore AS computation is based on the estimated complete matrix $\tilde{\mathbf{H}}'_{AB}$, i.e. by a certain AS criteria X, the selection can be expressed as:

$$\{\mathbf{F}_{A,opt}, \mathbf{F}_{B,opt}\} = \underset{\mathbf{F}_A, \mathbf{F}_B}{\arg\max}\, X(\mathbf{F}_B^H \tilde{\mathbf{H}}'_{AB}\mathbf{F}_A)\,. \qquad (6)$$

For example, if the criterion is the maximization of the capacity, $X(A)=\log|1+\boldsymbol{AA}^H SNR/n_A|$. If $\mathbf{F}_{A,opt}, \mathbf{F}_{B,opt}$ are selected based on the training phase, the equivalent channel in the data transmission phase becomes

$$\mathbf{H}_{eq} = \mathbf{F}^H_{B,opt}\mathbf{C}_{B,Rx}(\mathbf{F}_{B,opt})\mathbf{H}_{AB}\mathbf{C}_{A,Tx}(\mathbf{F}_{A,opt})\mathbf{F}_{A,opt}\,. \qquad (7)$$

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

$$\tilde{H}'_{AB} = \mathbf{C}_B^{(Rx)}\mathbf{H}_{AB}\begin{bmatrix} \alpha_{11}^{(Tx)} & & & \\ & \alpha_{22}^{(Tx)} & & \\ & & \alpha_{13}^{(Tx)} & \\ & & & \alpha_{24}^{(Tx)} \end{bmatrix}. \qquad (8)$$

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, during data transmission phase,

$$\tilde{\mathbf{H}}_{AB} = \mathbf{C}_B^{(Rx)}\mathbf{H}_{AB}\begin{bmatrix} \alpha_{11}^{(Tx)} & & & \\ & 0 & & \\ & & \alpha_{23}^{(Tx)} & \\ & & & 0 \end{bmatrix}, \qquad (9)$$

there will be a distortion caused by $\alpha_{13}^{(Tx)} \neq \alpha_{23}^{(Tx)}$, and 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 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 RF chain with antenna element at STA A, and all the possible RF responses can be expressed as:

$$\begin{array}{cccc} a_{11}^{(Tx)} & a_{22}^{(Tx)} & \cdots & a_{n_A n_A}^{(Tx)} \\ a_{12}^{(Tx)} & a_{23}^{(Tx)} & \cdots & a_{n_A(n_A+1)}^{(Tx)} \\ \vdots & \vdots & \ddots & \vdots \\ a_{1(N_A-n_A+1)}^{(Tx)} & a_{2(N_A-n_A+2)}^{(Tx)} & \cdots & a_{n_A N_A}^{(Tx)} \end{array}, \qquad (10)$$

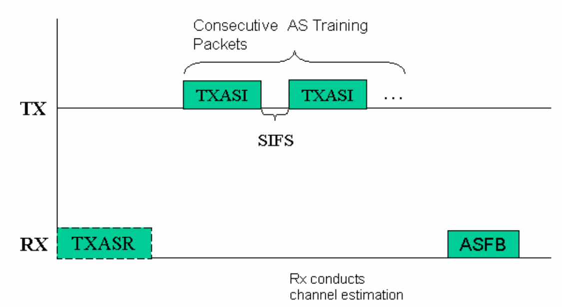

Figure 2. Transmit AS Training Example.

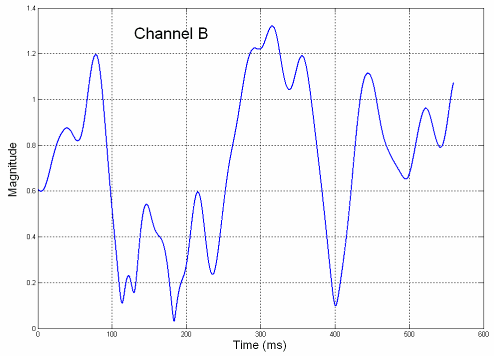

Figure 3. Time Variation in WLAN Channel Model B.

III. MAC-based AS Protocol

The low Doppler spread of WLAN channels (see Figure 3 for a WLAN channel realization [2]) allows us to propose a MAC-based AS training, in which the AS training phase is formed by a sequence of *M* consecutive training packets, each containing one of the *M* AS training fields transmitted from and/or received by one of the *M* disjoint antenna subsets. All the training information is signaled in MAC headers, where a dedicated high-throughput control field is already defined for signaling the new MIMO high-throughput features such as transmit beamforming and fast link adaptations [1]. Therefore the proposed training method greatly reduces the required modifications in the standard. Specifically, these training packets should be sent in burst, as illustrated in Figure 2, an example of transmit AS training only. This protocol can be described as follows: 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. Then the transmitter sends out $M = \lceil N_A / n_A \rceil$ consecutive AS training packets with short inter-frame interval (SIFS, equal to 16 μs [1]), each containing the regular long and short OFDM training fields in its preamble as defined in [1], and transmitted from one subset of n_A antennas. On receiving these packets, the receiver conducts channel estimations to establish the complete channel matrix in each subcarrier. Finally the receiver may either implement AS computation and feedback the selected antenna indices, or directly feeds back the complete channel matrices for the transmitter to conduct 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. Note that these AS training packets may also contain data payload. In that case, some "back-off" strategies, e.g. applying the lower level of modulation and coding schemes, are necessary, because the link adaptation output regarding the previously selected antenna subset is not valid after switching. 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 [8].

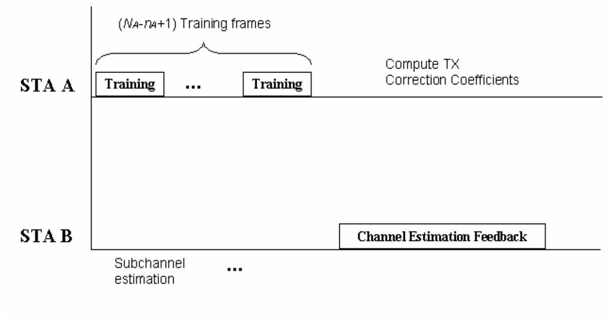

Figure 4. Transmit AS Calibration Process.

IV. AS with RF Imbalance

To recover the possible performance degradation caused by the RF imbalance problem, one 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 distortions due to channel Doppler (longer AS training phase).

Alternatively we propose a simple calibration process. Since the RF responses vary with the environment (e.g. carrier frequency drift, 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 timer intervals, e.g., only upon station association, or when the environment varies.

Figure 4 shows the calibration procedure for transmit AS. 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 (10). For example, the first training packet uses the connections:

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

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. 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 Figure 4. The correction coefficients are determined as follows: by ignoring channel estimation errors and assuming static channel during the transmission of all the AS calibration training packets,

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

where $\tilde{h}^{(li)}_{AB,j_B i} = \beta^{(Rx)}_{l_B j_B} h_{AB,j_B i} \alpha^{(Tx)}_{li}$ stands for the equivalent channel coefficient involving all the RF responses; $h_{AB,j_B i}$ is the actual physical channel coefficient from transmit antenna *i* to receive antenna j_B, which is connected to the predetermined receive RF chain l_B, with $\beta^{(Rx)}_{l_B j_B}$ the corresponding receive RF response. $\tilde{\mathbf{H}}'_{AB}(2) \ldots \tilde{\mathbf{H}}'_{AB}(N_A - n_A + 1)$ can be expressed similarly based on different transmit RF chain and antenna element connections following the corresponding rows in (10). For the *i*-th transmit antenna, we then do the following calculation:

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

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 (10). Then, κ_{li} is multiplied with the baseband signal transmitted from 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, transmit antennas 1 and N_A are always connected to RF chain 1 and n_A , respectively following the constraint in (10), so 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 can be expressed as:

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

there is no 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, and is equivalent to replacing the 1's in $\mathbf{F}_A$ or $\mathbf{T}_{\boldsymbol{A}}(m)$ 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 (10). 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 2 can be deployed without distortions.

Note that the above calibrations should be conducted in each (or each subgroup of) subcarrier(s) when applied in OFDM systems. Also, they can be straightforwardly applied when the connection constraints in (10) does not hold (i.e. L_i contains any RF chains for any antenna i). Finally, in WLAN the calibration frame exchange sequence in Figure 4 can be conducted by utilizing a normal AS training phase as in Figure 2, where the receiver should feedback CSI only. Consequently no extra signaling needs to be defined for calibrations.

V. Numerical Results

In the first scenario where $N_A = 4, n_A = 2,$ and $N_B = 2, n_B = 2$, we investigate the effectiveness of the MAC-based AS training method assuming that RF imbalance has no significant impact. We use 64-QAM and rate ¾ convolution channel coding (1/2 convolution code with puncturing [1]) as the modulation and coding set in each of the two transmitted data streams, with 20MHz bandwidth and a 0.8 μs 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 are no further impairment from time synchronization errors and RF imperfections such as carrier and sampling frequency offsets, phase noise, I/Q 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]. 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. 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). The parameter T_{AS} defines the length of the AS training cycle. 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 2×2 MIMO channel capacity over all subcarriers. From the packet error rate (PER) results in channel model B (Figure 5), 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 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 (5dB when $T_{AS} = 10ms$, and more than 1dB when $T_{AS} = 100ms$). 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 [5] and references therein.

In channel model E (Figure 6), 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 $T_{AS} = 10ms$), because the less correlated sub-carriers make different antenna subsets look more "even" with respect to the performance criterion (aggregated capacity or PER).

In the second scenario, RF imbalance is taken into considerations in channel B, where the PER of 2-

data stream WLAN system without AS, and MAC-based AS with and without calibration (both setting $T_{AS} = 10ms$), 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 $\pm 3dB$, and phase uniformly distributed in $\pm\pi$. We can then see from Figure 7 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 RF imbalance will degrade the performance of 2x2 MIMO without AS, hence the gains achieved by applying AS is even larger than in Figure 5.

V. Conclusions

In this paper we address two important issues for employing antenna selection techniques in emerging high throughput WLAN systems: AS training protocol and RF imbalance impairment mitigations. The proposed MAC-based AS training method minimizes the amount of amendments required for accommodating AS in the new 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, and have been adopted in the recently adopted preliminary version of the IEEE 802.11n baseline draft.

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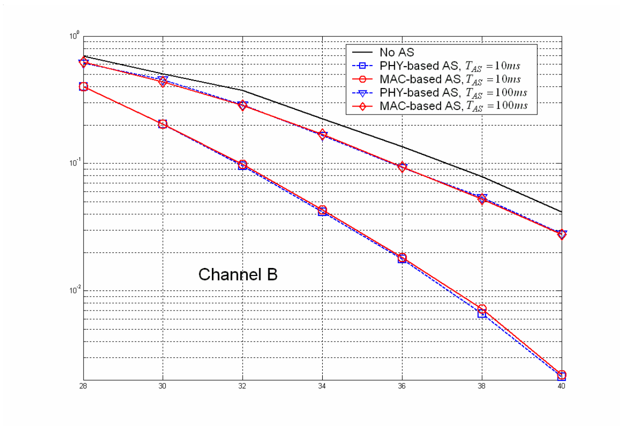

Figure 5. Results of Channel B

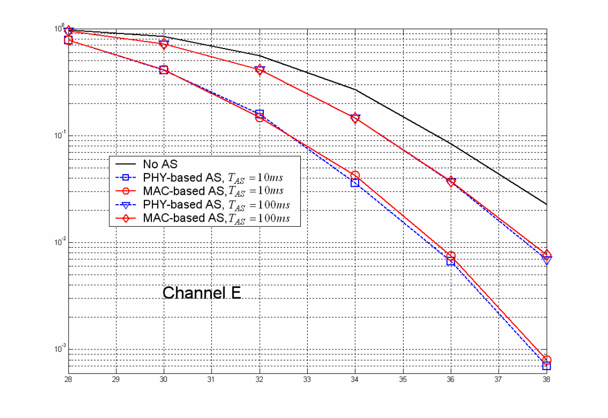

Figure 6. Results of Channel E

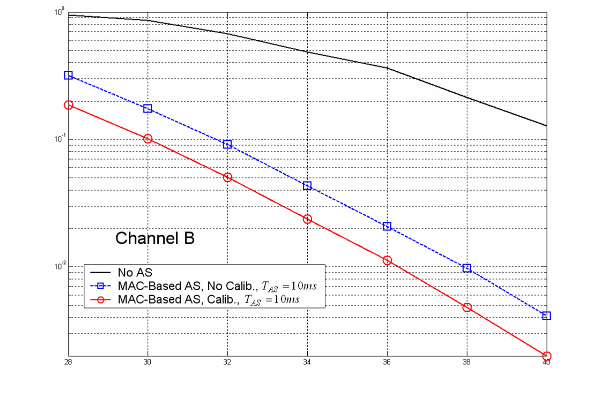

Figure 7. Results of Channel B under RF Imbalance