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## Abstract

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# Implementation Aspects of Antenna Selection for MIMO Systems

(invited paper)

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***Abstract*—Antenna selection is a promising technique for reducing complexity of multiple-antenna (MIMO) systems. In antenna selection, more antenna elements than RF transceiver chains are available for up-conversion and down-conversion. A subset of the available antenna elements is selected and connected to the RF chains. The reduction in the number of RF chains helps to reduce the implementation cost of multi-antenna systems. This paper considers a number of "practical" issues in the implementation of such systems. We discuss schemes for the channel estimation for all all antenna elements, and show that antenna selection is robust to channel estimation errors. RF preprocessing can be used to enhance the array gain of antenna selection schemes; the performance is robust to errors in the RF elements used for the preprocessing Finally, we analyze both bulk selection and per-tone selection in MIMO-OFDM systems, and show that the former is usually preferable. Results from simulations with 802.11n-compliant systems, and capacity results in measured channels show that SNR and capacity gains can be achieved with antenna selection in practical situations.**

## I. INTRODUCTION

MIMO (multiple input multiple output) systems use multiple antenna elements at both link ends. Given their ability to dramatically increase the spectral efficiency, suppress interference, and improve the robustness of transmission in wireless systems [1–3], MIMO system have received great attention in the last decade. It has been shown that, under certain assumptions about the propagation channel, the achievable capacity increases linearly with the number of antenna elements. Several practical schemes, which spatially multiplex multiple data streams from the different transmit antennas, have been proposed [4]. Practical MIMO schemes have also been proposed to enhance the robustness of data transmission to fading, e.g., linear transmit- and receive-diversity [5] and space-time coding [6].

Despite all these advantages, MIMO has been slow in getting adapted in practical wireless systems. Only now are the first standardized commercial systems emerging. One of the reasons for this slow adaptation is the considerable effort in terms of hardware required by MIMO. While antenna elements are cheap (often just a metallic rod or a piece of copper), each antenna element at the receiver requires a complete RF chain, including a low noise amplifier, a frequency down-converter, and an analog to digital converter. A similar effort is also required at the transmitter.

*Antenna subset selection* (also known as *hybrid antenna selection*) is a promising technique that mitigates the hardware complexity problem. In antenna subset selection, the number of available antenna elements ($N_\mathrm{t}$ at the transmitter and $N_\mathrm{r}$ at the receiver) is larger than the number of RF chains ($L_\mathrm{t}$ at the transmitter and $L_\mathrm{r}$ at the receiver). The RF chains are thus connected to a *subset* of the available antenna elements, with the choice of the subset depending on the state of the propagation channel. Antenna selection can be performed at the transmitter (transmit antenna selection, TAS), the receiver (RAS), or at both link ends (T-RAS). It has been shown that under most circumstances antenna selection systems have the same *diversity order* as full-complexity (FC) systems (which have as many RF chains as antenna elements, $N_\mathrm{t}$ and $N_\mathrm{r}$), and suffer from a small loss of *array gain* (mean SNR gain), while greatly reducing complexity.

Due to these advantages, antenna selection has been intensively studied. The information-theoretic capacity as well as the diversity performance of MIMO systems with linear transmit diversity and space-time coding has been analyzed in a number of papers (e.g., [7–17]). Methods to improve the array gain by means of preprocessing in the RF domain were suggested in [18–20]. A detailed review of those results as well as further references can be found in [21]. In this overview paper, we concentrate on the more practical aspects that are related to the actual implementation of antenna selection, and on the performance of antenna selection with realistic array constellations in measured propagation channels.

The remainder of the paper is organized as follows: in Sec. II, we review the principles of antenna selection, including fast algorithms for the selection of the best antennas, and the preprocessing for improved array gain. Next, in Sec. III, we discuss various implementation aspects. These include the design of training sequences so that the channel from all transmit to all receive antenna elements can be estimated, the impact of hardware non-idealities and imperfect estimation, use of array configurations that deviate from the "standard" uniform

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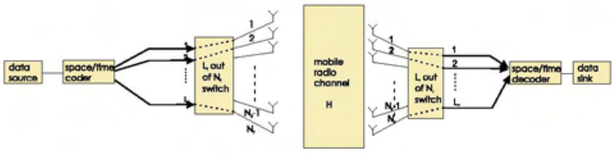

Fig. 1. Blockdiagram of a generic MIMO system with antenna selection. From [22].

linear array configuration, and system design in frequency-selective channels. Section IV presents results of simulations of IEEE 802.11n systems and capacity results for antenna selection based on measured propagation channels. A summary and conclusion in Sec. V wrap up this paper.

## II. PRINCIPLES OF ANTENNA SELECTION

### A. *Selection for spatial multiplexing and diversity*

Figure 1 shows a block diagram of a generic MIMO system with antenna selection. An $L_t$-element transmit signal vector is obtained from the source data by space-time coding and/or linear weighting. This signal is then mapped onto the selected transmit antenna elements, resulting in a transmit signal vector $\vec{s}$ that contains $L_t$ non-zero entries, and $N_t - L_t$ zero-value entries. This signal vector then passes through a MIMO propagation channel, which is represented by a transfer function matrix $\underline{H}$ of dimension $N_r \times N_t$, so that the received signal vector, $\vec{y}$, is

$$\vec{y} = \underline{H}\,\vec{s} + \vec{n} \qquad (1)$$

and $\vec{n}$ is the noise vector. The noise is assumed to be additive white zero-mean Gaussian with covariance $\sigma_n^2 \underline{I}_{N_r}$. The receiver then selects $L_r$ of the available $N_r$ signals for down-conversion and further processing. In Eq. (1), the propagation channel is assumed to be frequency-flat. Frequency-selective channels are treated in Sec. III-D.

When antenna selection is used, the information-theoretic capacity is given by

$$C_{\text{H-S/MIMO}} = \max_{S(\widetilde{\underline{H}})} \left( \log_2 \left[ \det \left( I_{L_r} + \frac{\overline{\Gamma}}{N_t} \widetilde{\underline{H}} \widetilde{\underline{Q}} \widetilde{\underline{H}}^{\dagger} \right) \right] \right), \qquad (2)$$

where $\overline{\Gamma}$ is the average SNR, and $\widetilde{\underline{H}}$ is a modified channel matrix of size $(N_t - L_t) \times (N_r - L_r)$ that includes the rows and columns of $\underline{H}$ that correspond to the selected antennas, and $\mathcal{S}(\widetilde{\underline{H}})$ is the set of all possible sub-matrices $\widetilde{\underline{H}}$. Here, $\underline{I}_{N_r}$ is the $N_r \times N_r$ identity matrix and $\widetilde{\underline{Q}}$ is the transmit signal covariance matrix. It is noteworthy that for transmit antenna selection in the absence of CSIT (except for information about which transmit antennas to use), $\widetilde{\underline{Q}} = \underline{I}_{L_t}$ is *no longer* optimum [10], [11]. However, this fact is usually ignored in the literature, and we will not take it into account for the remainder of the paper.

One of the key consequences of Eq. (2) is that the mean capacity, which determines the possible number of data streams, increases linearly with $\min(L_t, L_r)$. However, the slope of the capacity distribution, which determines the fading margin that guarantees a certain outage capacity for given a certain mean capacity, is determined by $N_t$ and $N_r$.

### B. *Channel characteristics and impact on selection*

Most of the theoretical analyses of antenna selection assume a highly simplified channel model in which the entries of the channel matrix $\underline{H}$ are independent, identically distributed complex Gaussian entries. Such a channel model can occur, for example, if the antenna arrays at transmitter and receiver are uniform linear arrays, the antenna elements have isotropic patterns, and the multipath components of the channel arrive from all directions. High theoretical capacities are possible for this channel model because its inherent heavy multipath allows for the transmission of multiple, independent data streams that can be spatially separated at the receiver.

While such channels provide a good theoretical benchmark, they rarely occur in practice. The following effects have to be taken into account for realistic system assessments:

1) *Signal correlation:* If the antenna elements at the transmitter and receiver are closely spaced, and/or the angular spread of the multipath components is small, then the entries of $\underline{H}$ are correlated. This case is often modeled by means of the so-called Kronecker model [23]

$$\underline{H} = \underline{R}_{\text{Rx}}^{1/2} \underline{G}_{\text{G}} \underline{R}_{\text{Tx}}^{T/2}, \qquad (3)$$

where $\underline{R}_{\text{Rx}}$ and $\underline{R}_{\text{Tx}}$ are the channel correlation matrices at the transmitter and receiver, respectively, and $\underline{G}_{\text{G}}$ is a matrix with i.i.d. complex Gaussian entries. We stress that this model is still a simplification as it does not reflect the dependence of the receive correlation matrix on the transmit directions, and vice versa. A more detailed model was recently proposed by [24]. The Kronecker model is often used for system simulations.

2) *Mutual coupling between antenna elements:* Mutual coupling can impact the performance of antenna selection systems [25]. The nature of this impact depends on the type of antenna matching (termination). Many antenna selection systems either use open-circuit terminations or 50 Ω matching.

3) *Unequal means:* If antennas with different patterns and/or polarization are used, the mean received power differs at the different antenna ports. Naturally, ports with higher power tend to be selected more often in an antenna selection scheme. Its impact on capacity and diversity is discussed in detail in Sec. IV.B.

### C. *Selection algorithms*

The number of possible choices of antenna subsets, $\binom{N_t}{L_t}\binom{N_r}{L_r}$, can be extremely large even for small numbers of available antennas and subset sizes. Therefore, several sub-optimal algorithms have been proposed to either reduce the number of choices to be considered or to simplify the optimization criterion for each choice.

*Optimality criterion:* For orthogonal space-time block codes, the optimality criterion is simple – it is the Frobenius norm of $\widetilde{H}$, which is the sum of the squares of the amplitudes of the elements of $\widetilde{H}$ [13]. The same criterion may also be used for selection in a space-time trellis code transmit diversity system. A weak justification for this was provided in [26], which showed that the criterion maximizes a lower bound on the pair-wise distance between codewords of the STTC. However, for spatial multiplexing systems, the norm-based criterion, which is also called the received signal strength criterion, is considerably sub-optimal at higher SNRs or in the presence of spatial correlation. Therefore, a simplified criterion that approximates the optimal spatial water-filling matrix was proposed in [27] for TAS. Simplified criteria that maximize the lowest SNR among all the streams were proposed for different linear receivers for RAS in [28, 29].

*Algorithms:* For spatial multiplexing, a fast decremental algorithm for receive antenna selection was proposed in [30]. It is based on the intuition that a row that is highly correlated with another row contributes little and may be removed. Iterative incremental (decremental) algorithms were proposed for receive antenna selection for spatial multiplexing in [31] ([32]) that add (remove) an antenna element in each step.

### D. *RF Preprocessing*

When antenna selection is used for open-loop or closed-loop diversity systems, the achievable diversity order $N_t N_r$ is as good as that of a full-complexity system. However, it does suffer from a loss in array gain. Novel RF preprocessing architectures, which are similar to conventional antenna selection in that they employ fewer RF chains, have been recently proposed to alleviate this problem [18–20]. At the receiver, the innovation lies in introducing an RF preprocessing matrix that processes received signals from the antennas; this is followed by selection (if necessary), down-conversion to baseband, and further signal processing. (An analogous set up can also be envisaged for RF post-processing at the transmitter.)

RF preprocessing circuits based on variable phase-shifters are familiar to the microwave community, which has used it for analog beamforming [33], for example. Various technologies such as Silicon or GaAs PIN diodes, GaAs FETs, ferro-electric materials, piezo-electric transducers (PET), and Micro-Electro-Mechanical Systems (MEMS) have been investigated for these phase-shifters. These differ in their insertion losses, chip area, operating voltage, carrier frequency and bandwidth, tuning times, etc.

Several preprocessing designs that are tailored to the CSI at the receiver are available. (i) *FFT-Selection (FFT-S) case:* This is the simplest case in which the preprocessing matrix is always fixed. For example, in [18], a Butler matrix is followed by a selection switch. While it outperforms conventional selection, its performance gain depends on the mean angle of arrival of the incoming signal. (ii) *Time-Variant (TV) case:* This achieves the best performance as the RF preprocessing matrix is tuned to the instantaneous channel state [19]. (iii) *Time-Invariant (TI) case:* This is an intermediate solution is one in which the RF preprocessing solution is based only on the slowly-varying large-scale statistics of the channel [20]. In this case, skipping the selection switch altogether is a feasible and attractive option. If the preprocessing matrix is followed by a selection switch, we refer to it as the TI-S case.

TABLE I

AVERAGE OUTPUT SNR (IN DB) COMPARISON OF RF PRE-PROCESSING ($N_T = N_R = L_T = 4$, $L_R = 1$, $\underline{R}_{TX} = \underline{I}_{N_T}$).FROM [20].

| | FC | TI-S | TI | FFT-Sel. | Ant. Sel. |
|---|---|---|---|---|---|
| $\theta_r = 45°, \sigma_r = 6°$ | 15.8 | 15.8 | 15.8 | 13.6 | 10.8 |
| $\theta_r = 60°, \sigma_r = 6°$ | 15.8 | 15.8 | 15.8 | 15.8 | 10.8 |
| $\theta_r = 60°, \sigma_r = 15°$ | 14.8 | 14.2 | 14.1 | 14.1 | 11.4 |

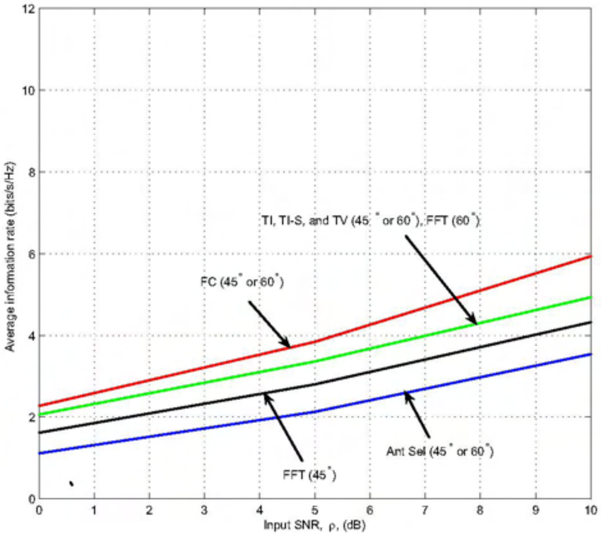

Fig. 2. Average information rate for spatial multiplexing system. Kronecker channel model with $\theta_r = 45°$, and $\sigma_r = 6°$ assumed ($N_t = L_t = 2$, $N_r = 4$, $L_r = 1$, $\underline{R}_{Tx} = \underline{I}_{N_t}$). From [20].

The optimal preprocessing matrices for TI and TV designs depend on whether spatial diversity (which maximizes output SNR) or spatial multiplexing (which maximizes information rate) is used. Approximations to the optimal solutions, which perform just as well and use only variable phase-shifters, were proposed in [19, 20].

For a closed-loop spatial diversity system based on maximum ratio transmission, Table I compares the performance of TI, TV, FFT-S, and conventional antenna selection with that of a full-complexity receiver for the Kronecker channel model. Different mean angles of arrival ($\theta_r$) and angle spreads ($\sigma_r$) are considered. Figure 2 compares the average information rates achieved by the above schemes when TI and TV are optimized for spatial multiplexing. In both systems, it can be seen that FFT-S, TI, and TV all significantly outperform conventional antenna selection, and, in some cases, perform as well as FC.

## III. IMPLEMENTATION ASPECTS

### A. *Antenna selection training*

The issue of training for antenna selection has received relatively little attention in the literature. In order to select the best subset, all the $N_t N_r$ links corresponding to all possible transmitter and receive antenna pairs need to be 'sounded', even though only $L_t$ and $L_r$ elements at the transmitter and receiver, respectively, will eventually be used for data transmission. In general, such sounding can be achieved with a switched approach. For simplicity, let us assume that $R_\mathrm{t} = N_\mathrm{t}/L_\mathrm{t}$ and $R_\mathrm{r} = N_\mathrm{r}/L_\mathrm{r}$ are integers. Then we can divide the available transmit (receive) antenna elements into $R_\mathrm{t}$ ($R_\mathrm{r}$) disjoint sets. The "switched" antenna sounding now repeats $R_\mathrm{t} \cdot R_\mathrm{r}$ times a "standard" training sequence that is suitable for an $L_\mathrm{t} \times L_\mathrm{r}$ MIMO system. During each repetition of the training sequence, the transmit (receive) RF chains are connected to different sets of antenna elements. Thus, at the end of the $R_\mathrm{t} \cdot R_\mathrm{r}$ repetitions, the complete channel has been sounded. In case of transmit antenna selection in frequency division duplex systems in which the forward and reverse links are not identical, the receiver feeds back the optimal subset to the transmitter. However, in reciprocal time division duplex systems, the transmitter can do this on its own.

The switched training precedure increases the overhead of a system that employs antenna selection. Moreover, the training needs to be done quickly (within the channel's coherence interval) in order for it to be useful. In wireless LANs for indoor applications, the channels vary very slowly. This is exploited in the design of a low overhead *MAC-based* antenna selection training protocol in the IEEE 802.11n draft specification [34]. Instead of extending the physical (PHY) layer preamble to include the extra training fields (repetitions) for the additional antenna elements, antenna selection training is done by transmitting and receiving packets by different antenna subsets. As training information (a single standard training sequence for an $L_\mathrm{t} \times L_\mathrm{r}$ MIMO system) is embedded in the MAC header field, the packets can carry data payloads, which keeps the training overhead to a minimum. The time available for switching between the antenna subsets is now the guard time between packets, which is of the order of microseconds. This enables the use of slower, MEMS-based, switches, which have extremely low insertion loss.

In fast-varying channels, selection can be done on the basis of channel statistics (e.g., fading correlations), whose variation is orders of magnitude slower than that of fading. It was shown in [35] that such an antenna selection approach is effective in highly correlated channels.

### B. RF mismatch

One implementation problem that has largely been ignored in the selection literature is RF imbalance. RF imbalance occurs because the RF parameters for different connections of antenna elements and RF chains at the transmitter and the receiver are different [36]. Unless compensated for, different connections will result in different baseband channel estimates, even though the underlying physical MIMO channel matrix, $\underline{H}$, is the same.

An over-the-air calibration process, which involves communication between the transmitter and the receiver, is therefore required. Training sequences are used to 'calibrate' each possible connection of antenna element with an RF chain. This results in connection-specific *calibration coefficients* that can be used to compensate for the RF imbalance when receiving data. In the absence of cross-talk among the RF chains complete compensation is achieved by simply multiplying the baseband signals at the transmitter and receiver with the corresponding calibration coefficients.

TABLE II

AVERAGE INFORMATION RATE WITH IMPERFECT CSI FOR $\theta_r = 45°$ AND $\sigma_r = 15°$. ($N_\mathrm{T} = N_\mathrm{R} = L_\mathrm{T} = 4$, $L_\mathrm{R} = 1$, $\underline{R}_\mathrm{TX} = \underline{I}_{N_\mathrm{T}}$).FROM [37].

| $\sigma_H$ | FC | TV | TI | Ant. Sel. |
|---|---|---|---|---|
| 0 | 5.78 | 3.70 | 3.47 | 2.61 |
| 0.6 | 5.78 | 3.52 | 3.46 | 2.45 |

TABLE III

AVERAGE INFORMATION RATE WITH PHASE QUANTIZATION AND CALIBRATION ERROR FOR $\theta_r = 45°$ AND $\sigma_r = 6°$ ($N_\mathrm{T} = N_\mathrm{R} = L_\mathrm{T} = 4$, $L_\mathrm{R} = 1$, $\underline{R}_\mathrm{TX} = \underline{I}_{N_\mathrm{T}}$). FROM [37].

| Resolution | FC | TV (0°) | TV (±10°) | TI (0°) | TI (±10°) | Ant. Sel. |
|---|---|---|---|---|---|---|
| Ideal | 4.65 | 3.86 | 3.85 | 3.86 | 3.85 | 2.43 |
| 3 bit | 4.65 | 3.80 | 3.80 | 3.78 | 3.77 | 2.43 |
| 2 bit | 4.65 | 3.61 | 3.60 | 3.56 | 3.55 | 2.43 |

As each possible connection needs to be calibrated, the training overhead is greater. However, this needs to be done very infrequently (usually only upon association to the network).

### C. Non-idealities in selection

In addition to RF imbalance, several non-idealities in both hardware and software (signal processing) exist in a practical implementation. It is important to understand how robust antenna selection is to them as they can potentially diminish its advantages. For example, the introduction of a selection selection switch leads to an insertion loss. In RF preprocessing designs, the phase-shifter elements can suffer from phase and calibration errors. Last, but not least, imperfect channel estimates and feedback that occur due to noise during channel estimation and in feedback channels, respectively, can lead to selection of sub-optimal subsets and degrade performance.

Table II compares the average information rate achieved by the various RF preprocessing receiver architectures in the presence of imperfect selection which is modeled by adding Gaussian noise of variance $\sigma_H$ to the channel matrix before selection. It can be seen that antenna selection and RF preprocessing with antenna selection are both quite robust to imperfect channel estimates [37].

The average information rates of TV and TI, when implemented using only variable phase-shifters with finite phase resolution are plotted in Table III. A 2-bit phase shifter changes phases in steps of 90°, while a 3-bit one does so in steps of 45°. Calibration errors (0° and ±10°) are also considered. It can be seen that RF preprocessing is extremely robust to phase and calibration errors.

The key issue that affects the performance of selection is the insertion loss introduced by the additional RF elements. A 2 dB insertion loss in the phase shifter elements reduces the TI capacity to that of ideal FFT-selection, while a 5 dB loss reduces it to that of antenna selection itself [37]. For higher insertion losses, it might be necessary to place the LNAs before RF preprocessing or selection elements, which can increase the cost of the system.

Reference [12] showed that the performance loss due to imperfect channel estimation is negligible so long as the pilot power is above a certain threshold. However, the loss increases rapidly for lower pilot powers. However receive subset selection with one transmit antenna achieves the full diversity order (at large SNRs) even with imperfect channel estimates [38]. Antenna selection verification and signaling optimization to handle feedback errors in transmit antenna selection was studied in [39].

### D. *Bulk versus tone selection in OFDM*

For operation in frequency-selective channels, MIMO is usually combined with OFDM (orthogonal frequency division multiplexing). OFDM transmits the information on many (overlapping but orthogonal) subcarriers so that each subcarrier (tone) sees a flat-fading channel. Now Eq. (1) is valid for each tone separately, as the channel matrix $\underline{H}$ depends on the tone.

In a MIMO-OFDM system with antenna selection, the optimum antenna subsets can vary from tone to tone. Thus, two types of antenna selection are possible: (i) bulk selection, where the selected antenna subset is used for *all* OFDM sub-channels, and (ii) per-tone selection, where a different subset can be used for each tone. Naturally, the second solution requires a much higher complexity: the signals from all antenna elements have to be converted to/from baseband, and the selection is implemented in baseband.

Per-tone selection thus does not save hardware (when compared to full-complexity systems), but only simplifies the signal processing and reduces the feedback, as transmit selection can be viewed as (coarse) precoding. We will also see in Sec. IV-B that the performance difference between the two schemes is not large. Thus, bulk selection will be the method of choice in most applications.

## IV. MEASUREMENTS AND SIMULATIONS

### A. *Simulations of 802.11n systems*

In this section, we present simulation results for the performance of real-world MIMO systems with antenna selection. The emphasis lies on the IEEE 802.11n Wireless LAN standard, since it is among the first that includes antenna selection [34].

Figure 3 compares the packet error rate (PER) performance of a 2x2 MIMO system with that of a system that uses transmit antenna selection and selects 2 out of 4 antenna elements. The performance of both MAC-based and PHY-based selection training (see Sec. III-A) is considered. The parameter $T_{\mathrm{as}}$ is the duration between two adjacent antenna selection training phases. The channel model E [40] is used in the simulations that are conducted on our in-house software test-bed, which is built as per the PHY and MAC specifications in [34]. The results are shown for 64-QAM modulation with rate 3/4 convolutional codes applied to the two spatially multiplexed data streams.

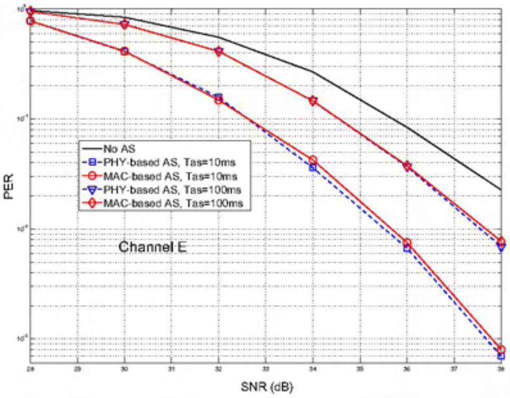

Fig. 3. Packet error rate of a (simplified) 802.11n system with antenna selection with various transmission time intervals between training sequences. Channel model: Channel E of the 802.11n channel models. From [36].

The antennas are selected based on a capacity-maximization criteria, which is sub-optimum for 802.11n systems as they use a limited modulation alphabet. We assume that there is no insertion loss due to the selection switch and that the RF imbalances are properly calibrated and compensated for. Impairments due to time and frequency synchronization errors are not considered.

We can see that antenna selection improves performance over the no-selection case by 3 dB at high SNR. Both PHY-based and MAC-based training schemes achieve almost the same performance. Given its advantages, such as relaxed switching speed and reduced insertion loss, MAC-based training is therefore preferable in high speed WLANs.

### B. *Measurement-based capacity analysis*

To assess the impact of realistic antenna configurations and propagation channels, we performed measurements of the transfer function matrix with mock-up laptops (PC), access points (AP), and hand-held devices (HH). The antenna arrangement on the different devices are shown in Fig. 4, together with the orientation of the devices in which the measurements were taken. Measurements were made for line-of-sight (LOS) scenarios (high Rice factor) and non-LOS (NLOS) scenarios. Capacity distributions were obtained by inserting the measured transfer function matrices into the capacity equation in Eq. (2). More details about the measurement setup and the simulation procedure can be found in [41].

In Fig. 5 the average capacity in flat-fading channels for seven different antenna selection schemes are presented: (i) full-complexity, (ii) antenna selection with optimum RF-preprocessing with instantantaneous CSI [19] as described in Sec. II.D (PSS opt), (iii) a suboptimum version thereof (PSS s-opt), (iv) antenna selection with FFT-preprocessing [18] as described in Sec. II.D (FFTS), (v) conventional antenna selection with the optimum selection algorithm (HS-B), (vi) con-

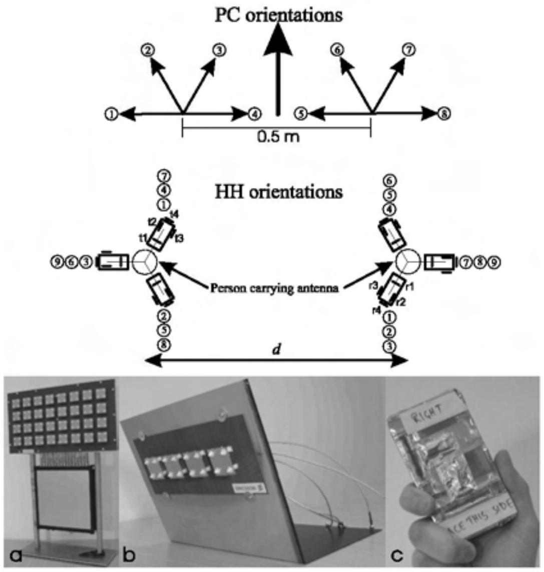

Fig. 4. Laptop (PC) and handheld (HH) orientations. Pictures of: (a) AP, (b) PC and (c) one of the two identical HH devices. From [41].

ventional antenna selection with the norm-based selection algorithm (PBS), and (vii) random antenna selection (HS-R). The same antenna selection algorithm was used at both ends of the link. We first observe that the capacity of the full-complexity scheme is considerably higher than with any of the antenna selection schemes. This is due to the larger number of spatial streams that the full-complexity scheme can transmit. For the AP-PC scenario, we find that for the same receive SNR, a smaller Rice factor and a larger angular spread increases the capacity – a result that is well known. However, we find that in the HH-HH case, the capacity is almost identical for the LOS and the NLOS case. This is due to the fact that the antennas on the HH have different orientations (and polarizations), so that signals are essentially decorrelated even in the LOS case. Furthermore, we find that the capacity is much smaller in the HH-HH case than in the AP-PC case. This is due to the fact that in the former case, the mean power at the different antenna elements is significantly different.

Optimum preprocessing (using instantaneous channel-state information) followed by selection increases capacity by 13% and 18% compared to pure antenna selection for the AP-PC and HH-HH configurations, respectively. FFT-S preprocessing shows a small gain for the LOS AP-PC scenario (note that due to the measurement setup, even the LOS scenario did not show a high Ricean K-factor). Its performance decreases for the HH-HH scenario because the antennas do not form "physically reasonable" beams, but create a rather arbitrary array pattern at the FFT outputs. Furthermore, the FFT tends to "smear" the power across the FFT outputs (this decreases the effectiveness of antenna selection).

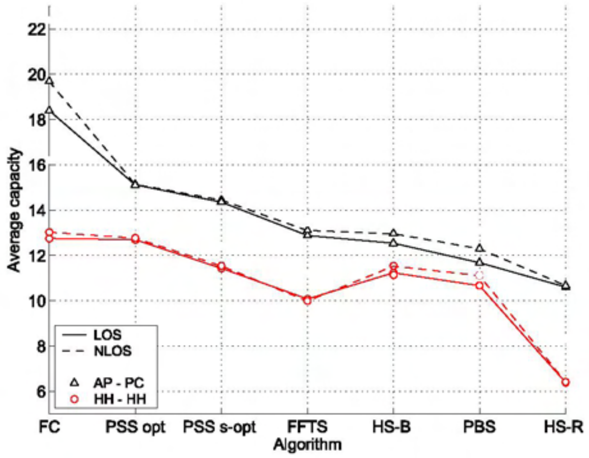

Fig. 5. The average capacity for the different antenna selection schemes are presented. Both AP-PC ($8:4\times4:2$ vertical polarized element on both sides, line configuration) and HH-HH ($4:2\times4:2$ single polarized elements) results are presented for LOS and NLOS [42].

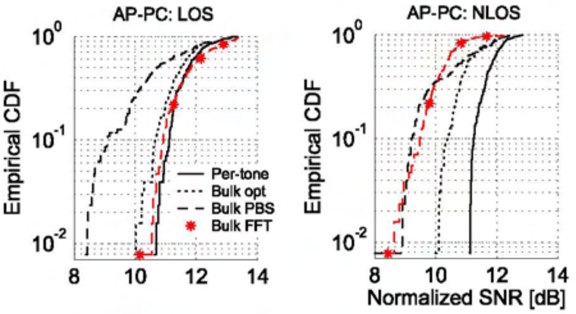

Fig. 6. The CDF of SNR averaged over sub-channels for the AP-PC scenario for both LOS and NLOS scenarios (configurations for AP-PC Line: H, V, Alt HV, DP). $8:4\times4:2$. Bulk selection and per-tone selection are compared. The effect of FFT pre-processing is also presented [42].

In Fig. 6 the CDFs of the SNR (assuming optimum diversity with CSI at the transmitter and the receiver, i.e., maximum-ratio transmission and maximum-ratio combining), averaged over the sub-channels within the selected bandwidth, are presented for bulk selection and per-tone selection. AP-PC channels are considered for both LOS and NLOS scenarios. The frequency bandwidth is 200 MHz. The results show that: (i) In an LOS scenario, bulk selection has a smaller performance loss compared to per-tone selection than in an NLOS scenario. This is due to the smaller variations in the used subsets over frequency. (ii) For LOS scenarios, FFT preprocessing recovers the array gain loss of antenna selection.

## V. SUMMARY AND CONCLUSIONS

We gave an overview of antenna selection for MIMO systems, with an emphasis on its practical implementation aspects. The main conclusions are the following:

- The diversity order of antenna selection systems is determined by the number of antenna elements. Furthermore, almost optimum array gain can be achieved by appropriate preprocessing of the signals in the RF domain.
- The number of spatial streams that can be transmitted is determined by the number of available RF chains.
- Appropriate training methods are vital to ensure the good performance of antenna selection. Their structure (delay between training fields, MAC-based vs. PHY-based) de-

pends on the channel variability and the system parameters.

- For WLANs, slow (MAC-based) training shows excellent performance.
- RF imbalances in the down-conversion chains have to be properly calibrated and compensated for.
- Antenna selection is robust to imperfect channel estimates. RF preprocessing is robust to phase and calibration errors. The key issue is insertion loss.
- In frequency-selective channels, selecting the same antennas for all frequencies (bulk selection), performs almost as well as per-tone antenna selection, and has a much lower hardware complexity.

Keeping these conclusions in mind, antenna selection is an eminently practical scheme that can greatly reduce the hardware effort in MIMO systems while retaining their excellent performance.

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