DIVERSITY AND MULTIPLEXING TECHNIQUES OF 802.11n WLAN

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Abstract – This paper is to analyze an improvement in performance of WLAN (Wireless Local Area Networks) systems introduced by space and space-time diversity, as well as spatial multiplexing. These MIMO (Multiple-Input Multiple-Output) techniques are implemented in today’s “pre-N” hardware, and will be approved in the emerging 802.11n specification. In order to perform the experiment, a Matlab application, that simulates WLAN physical layer, has been developed.

Index Terms – Signal processing, MIMO systems, diversity schemes, coding, modulation.

I. INTRODUCTION

Common WLAN standards defined by IEEE operate in the ISM (Industrial, Scientific, Medical) bands, i.e. 2.45 GHz and 5 GHz. OFDM (Orthogonal Frequency Division Multiplexing) is applied to overcome intersignal interference (ISI). The transmission runs in a frame mode. Numerous Modulation and Coding Schemes (MCS) are provided, which are switched by the transmitter adaptively, according to the channel condition.

The new specification of WLAN systems [1] introduces many techniques to improve data rate in the physical layer. Apart from modification of OFDM symbol (52 subcarriers dedicated for data transmission instead of 48 in 802.11a/g, shorter guard interval), two groups of methods can be distinguished: with backward signaling and without it. The first group comprises beamforming, i.e. the transmitter forms the signals in such a way, that their performance at the receiver’s input is optimized, on the basis of knowledge of the channel state. These methods are not considered in the paper, which focuses on the space and space-time diversity techniques. Spatial multiplexing is also addressed.

Some results of multi-antenna OFDM systems have been delivered in few articles, e.g. [2]-[3]. They can be treated as a reference to the present work to verify the accuracy of the Matlab simulation environment.

The article is organized as follows: Section 2 reviews space and space-time diversity techniques, while Section 3 refers to spatial multiplexing. The simulation results are presented in Section 4. Finally, Section 5 concludes the work.

II. SPACE AND SPACE-TIME DIVERSITY SCHEMES

The aim of space and space-time diversity is to improve radio link quality, using MIMO technology. In the first place, the systems with only receive diversity will be considered. Afterwards, a smart idea of Space-Time Block Coding (STBC) [4], which is proposed by 802.11n specification, will be examined. A general model of the transmitter and the receiver of a system employing space (space-time) diversity is shown in Fig. 1. At the transmitter adjacent data bits are encoded by a convolutional encoder. Consecutive codewords are distributed among adjacent subcarriers according to block interleaving rule, after which they are mapped onto constellation signals \( C_k(p) \), where \( k \) is the number of subcarrier and \( p \) denotes the number of OFDM symbol.

The STBC encoder (if implemented) takes the consecutive constellation signals \( C_k(p) \) and \( C_k(p+1) \), occupying a given subcarrier \( k \), which fall to \( p \)th and \( (p+1) \)th OFDM symbol, and creates their modified copies. All the signals are transmitted according to the orthogonal Alamouti scheme [4], i.e. the first antenna transmits \( C_{k1}(p) = C_k(p) \) and \( C_{k1}(p+1) = -C_k(p+1) \) on \( p \)th and \( (p+1) \)th OFDM symbol, respectively. Simultaneously, the second antenna transmits \( C_{k2}(p) = C_k(p+1) \) and \( C_{k2}(p+1) = C_k(p) \). The constellation signals to be transmitted via second antenna are cyclically rotated, according to 802.11n specification, but this operation does not lead to further diversity gain.

If space-time diversity is not implemented, STBC block is “transparent”, i.e. \( C_{k1}(p) = C_k(p) \), \( C_{k1}(p+1) = C_k(p+1) \), etc. In this case only one stream is transmitted.

Next, OFDM is realized with Inverse Fast Fourier Transformation (IFFT). Finally, Cyclic Prefix is added to avoid intersignal interference. In the “hardware” realization, Digital/Analog conversion and carrier modulation should be done before the signals are transmitted. These steps can be omitted in simulations, since the transmission in baseband channel is considered.

At the receiver, after Cyclic Prefix removal (CPR) and OFDM demodulation (FFT algorithm), each subchannel in frequency domain is ideally estimated, i.e. the frequency responses \( H_{km} \) of the subchannel between \( m \)th transmit and \( n \)th receive antenna at \( k \)th subcarrier are calculated for all \( m,n,k \). If the frequency response does not vary while a data

![Figure 1. Transmitter and receiver of system exploiting space (space-time) diversity](image-url)
frame is transmitted, the time index \( p \) can be omitted. The signal received from \( \eta \)th antenna at \( k \)th subcarrier in \( p \)th OFDM symbol is
\[
R_{kn}(p) = \sum_{m} H_{km} C_{km}(p) + \eta_{kn}(p),
\]
where \( C_{km}(p) \) is the signal transmitted from \( \eta \)th antenna at \( k \)th subcarrier in \( p \)th OFDM symbol, \( \eta_{kn} \) is a component representing additive noise. Diversity combiner computes estimates of transmitted signals (denoted by \( \tilde{C}_{k}(p) \)), in a way depending on employed diversity scheme and delivers modified channel estimates \( \tilde{H}_{k} \) to the Maximum Likelihood detector, which makes decisions about transmitted codewords. Finally, deinterleaved bits are decoded by the Viterbi decoder.

A. Receive diversity

The following diversity algorithms are to be examined: Antenna Selection, Subcarrier Selection, Equal Gain Combining (EGC) and Maximal Ratio Combining (MRC). Since only one transmit and two receive antennas are used, let us denote \( \mathbf{H}_{d}(p) = [H_{11}(p) ... H_{64}(p)] \), \( \mathbf{R}_{i}(p) = [R_{1}(p) ... R_{64}(p)] \), \( \mathbf{\tilde{C}}(p) = [\tilde{C}_{1}(p) ... \tilde{C}_{64}(p)] \), and finally \( \mathbf{H}(p) = [H_{1} ... H_{64}] \).

1) Antenna Selection: The diversity combiner selects the signal from the antenna with higher average power. Thus
\[
\mathbf{\tilde{C}}(p) = \mathbf{R}_{i}(p) \quad \text{and} \quad \mathbf{H}(p) = \mathbf{H}_{1} \quad \text{if} \quad \sum_{m}|H_{11}|^{2} > \sum_{m}|H_{21}|^{2}. 
\]
Otherwise, \( \mathbf{\tilde{C}}(p) = \mathbf{R}_{2}(p) \) and \( \mathbf{H}(p) = \mathbf{H}_{2} \).

2) Subcarrier Selection: The choice of antenna is made separately for each subcarrier, \( k \), depending on the magnitude response. In consequence \( \mathbf{\tilde{C}}_{k}(p) = R_{k1}(p) \) and \( \tilde{H}_{k}(p) = H_{k1} \), if \( |H_{k1}| > |H_{k2}| \). Otherwise \( \mathbf{\tilde{C}}_{k}(p) = R_{k2}(p) \) and \( \tilde{H}_{k}(p) = H_{k2} \).

3) Equal Gain Combining (EGC): the signals from both receive antennas are exploited, i.e. they are added after compensation of phase offsets:
\[
\mathbf{\tilde{C}}_{k}(p) = R_{k1}(p)\exp(-j\arg(H_{k1})) + R_{k2}(p)\exp(-j\arg(H_{k2})).
\]
Consequently \( \tilde{H}_{k} = |H_{k1}| + |H_{k2}| \). The same operation is done for each subcarrier.

4) Maximal Ratio Combining (MRC): this technique is very similar to EGC. The only modification is that the signals from both antennas are weighted according to their power. Hence \( \mathbf{\tilde{C}}_{k}(p) = R_{k1}(p)\tilde{H}_{k1} + R_{k2}(p)\tilde{H}_{k2} \) and \( \tilde{H}_{k} = |H_{k1}| + |H_{k2}| \).

B. Space-Time Block Codes

In case of space-time coding, the diversity combiner computes the estimates of transmitted constellation signals again. It is done with a following routine. The signals received by particular antennas in consecutive timeslots \( p \) and \( p+1 \) can be written as:
\[
R_{21}(p) = H_{k1}C_{k1}(p) + H_{k2}C_{k2}(p+1)e^{j\phi} + \eta_{k1}(p) \\
R_{21}(p+1) = -H_{k1}C_{k1}(p+1) + H_{k2}C_{k2}(p)e^{j\phi} + \eta_{k2}(p) \\
R_{22}(p) = H_{k1}C_{k1}(p) + H_{k2}C_{k2}(p+1)e^{j\phi} + \eta_{k2}(p) \\
R_{22}(p+1) = -H_{k1}C_{k1}(p+1) + H_{k2}C_{k2}(p)e^{j\phi} + \eta_{k1}(p+1)
\]
The factor denoted \( e^{j\phi} \) represents the phase rotation, provided by 802.11n specification, which has to be eliminated by the receiver. The author proposes to modify the original routine of diversity combiner [4] as follows:
\[
\tilde{C}_{k}(p) = H_{k1}^{*}R_{k1}(p) + H_{k1}^{*}(R_{k1}(p+1)e^{j\phi}) \\
+ H_{k2}^{*}R_{k2}(p) + H_{k2}^{*}(R_{k2}(p+1)e^{j\phi}) \\
\tilde{C}_{k}(p+1) = H_{k1}^{*}R_{k1}(p+1) - H_{k1}^{*}(R_{k1}(p+1)) \\
+ H_{k2}^{*}R_{k2}(p+1) - H_{k2}^{*}(R_{k2}(p+1))
\]
and it can be proved that each of these combined signals relates to a single transmitted signal only. Phase rotations do not affect the diversity gain. In case of 2x1 STBC system the components associated with signals received from the second antenna in (3) should be omitted.

III. SPATIAL MULTIPLEXING

Spatial multiplexing offers higher data rate than any of analyzed diversity techniques. The transmitter and receiver structures are shown in Fig. 2. Consecutive bits outgoing from the encoder are distributed among particular space streams and are subject to constellation mapping, cyclic shift and IFFT.

As two independent signals are transmitted simultaneously from numerous antennas, they interfere with one another at the input of receiver. To overcome this disadvantage, simple Zero Forcing combiner is employed, which estimates values of signals \( \mathbf{e}(p) = [c_{1}(p) ... c_{64}(p)] \), which are transmitted from antennas \( 1 ... m \) at \( k \)th subcarrier. Let us denote \( \mathbf{\mathcal{R}}(p) = [R_{1}(p) ... R_{64}(p)] \) and
\[
\mathbf{\mathcal{X}}_{k}(p) = [H_{k1}(p) \ldots H_{km}(p)] \\
\quad : \quad : \quad : \quad : \quad : \\
\quad H_{km}(p) \quad \ldots \quad H_{km}(p)
\]
It is noticeable that
\[
\mathbf{\mathcal{R}}(p) = \mathbf{\mathcal{X}}_{k}(p) \mathbf{\mathcal{C}}_{k}(p) + \mathbf{\eta}(p).
\]
Thus to recover the transmitted constellation signals, \( \mathbf{\mathcal{R}}(p) \) is multiplied by the inverse channel matrix \( \mathbf{\mathcal{X}}_{k}^{-1}(p) \). The inverse Cyclic Shift is not shown in Fig. 2 for its readability. It should be placed after FFT operation. After ZF combining, the signals are demapped and deinterleaved, as for diversity techniques, but separately in particular space streams. Finally, demulti-
plexed bits are decoded.

IV. SIMULATION RESULTS

A. Simulation setup

All time parameters are taken the same as in 802.11n draft 3.0 specification [1]. Transmission runs in 20 MHz bandwidth mode, 52 subcarriers are dedicated for data transmission, 4 of them are assigned to pilot signals. Encoder of [171 133]_HCT polynomials, without puncturing is employed (it results in data rate of \( \frac{1}{2} \)). Two modulation schemes are considered: QPSK and 16-QAM. The average total power is 1 W, independently of the number of transmit antennas, for a fair comparison.

There is a subchannel between each transmit and receive antenna, which is simulated according to the 11-tap exponential model (see e.g. [5]) with root mean square delay spread \( \tau_{\text{rms}} \) of 92.435 ns. Thus it is similar to ETSI channel B [6], but much easier to implement. The average power delay profile of the assumed channel is shown in Fig. 3. The randomly generated fading coefficients are normalized to achieve unitary average signal power at the input of each receive antenna.

The Doppler effect, being a result of continuous change of transmission environment, has been neglected. To justify this approach let us assume the terminal speed \( v = 3 \text{ km/h} \) and carrier frequency \( f_c = 2.45 \text{ GHz} \). Then the maximum Doppler shift is \( f_{\text{Dmax}} = \frac{v}{c} \approx 6.8 \text{ Hz} \) (\( c \) is the speed of light). In the auto-regressive channel model (see e.g. [7]), the time-domain channel response of \( j \)th tap of the subchannel at discrete time \( t+iT_i \) is

\[
g_j(t+iT_i) = \alpha_j g_j(t) + w_j(t+iT_i)
\]

where \( \alpha_j = \epsilon(g_j(t)g_j^*(t+iT_i)) = J_0(2\delta_{\text{Dmax}}iT_i) \), \( \epsilon(\bullet) \) denotes the expected value, \( J_0(\bullet) \) is the zeroth-order Bessel function of the first kind, \( w_j(t+iT_i) \) is an independent complex Gaussian random variable with zero mean and variance \( \sigma_i^2 = 1 - \alpha_i^2 \), and \( T_i \) is the sample time. As the worst case, 4096 information bytes per frame are to be transmitted at mode 1 (BPSK) without spatial multiplexing. Resulting number of OFDM symbols is 1261, that gives 100880 samples in time domain (including cyclic prefix). The auto-correlation value of tap responses falling to a frame declines from 1 to 0.988. It proves that the Doppler effect can be neglected. Assuming that each frame is transmitted in different channel condition due to random channel access, fading coefficients are generated independently for each frame.

B. Results

First, let us consider Single-Input Single-Output systems (MCS = \{1, 3\}). The BER curves for 16-QAM and QPSK are presented in Fig. 4.a and Fig. 5.a, respectively, by thin solid lines. The curves are asymptotically parallel, since both systems have the same number of antennas. The higher modulation order, i.e. the number of bits mapped onto constellation point, the worse BER performance. But it does not mean, that 16-QAM is worse than QPSK in any case. To make the comparison fair, higher data rate of the former should be taken into account. Moreover, a metric based on the Frame Error Rate is more valuable than the BER, since in case of any error appearance in a frame, retransmission must be ordered. Thus \( \text{Throughput} = \frac{R}{1-\text{FER}} \), where \( R \) denotes the data rate is a proper metric. Charts relating to the throughput are shown in Fig. 4.b and 5.b respectively. Notation of particular curves is the same as before. It turns out that 16-QAM system outperforms the QPSK one for SNRs > 19 dB, giving higher throughput.

The receive diversity schemes reviewed in section 2 have been examined for 16-QAM and QPSK. It is noticeable that Antenna Selection is rather an inferior technique, while the others significantly improve data link quality (higher slope of BER curve, gain of about 10 dB around the BER of \( 10^{-6} \)). The difference in BER between particular algorithms is negligible, but only EGC and MRC are comparable with each other in the throughput, so there is a suggestion to employ Equal Gain Combining, as it has easier implementation.

For comparison, 2x1 and 2x2 systems with STBC have been analyzed. The BER and throughput curves are shifted right by about 3 dB in comparison with EGC. It is justified by the fact, that the total transmitted power is normalized. In consequence the power per receive antenna is still the same, and hence the systems with multiplied receive antennas perform better. Therefore receive diversity techniques are more advantageous than Space-Time Block Coding, the more so as the former are easier to implement. Nevertheless space-time codes are still useful to set a system with diversity only at one (Access Point’s) side.

Performance of 2x2 STBC 16-QAM system has been examined. It appears to be much better than any 1x2 or 2x1 system, since the signals are transmitted through 4 independent subchannels (additive noise varies from one sample time to another). SNR gain of about 15 dB around the BER of \( 10^{-6} \) is observed in comparison with SISO system.

Finally, advantages of spatial multiplexing have been examined. The BER and throughput curves of 2x2 and 4x4 16-QAM (MCS = \{9, 27\}) as well as 2x2 QPSK (MCS = 11) systems are shown in Fig. 4 and Fig. 5, respectively. As can be noticed, the multiplexed systems offer the same BER performance as 1x1 ones, asymptotically. At low SNRs the signal detection is destroyed by the additive noise, which is gained, while multiplexing by \( ZF^i(p) \) by ZF combiner. In the region of high SNRs, the throughput is
higher than for the 1x1 system, proportionally to the number of space streams at both sides of the system.

V. CONCLUSIONS

In this paper some transmit and receive diversity algorithms, developed in 802.11n specification, have been analyzed. MIMO techniques have appeared to be powerful tools to enhance data rate in any channel conditions. Thanks to 2x1 Space-Time Block Codes, the system with antennas doubled at Access Point’s side only can improve performance in forward and reverse transmission. Spatial multiplexing enhances the throughput, but it fails in poor channel conditions, which is a result of ZF combiner usage. To overcome this disadvantage other algorithms, such as Minimum Mean Square Error (MMSE) and OSIC (Ordered Successive Interference Cancellation) should be examined in the future.

The conclusions, the author arrived at, agree with the earlier works related to MIMO-OFDM schemes. Thus the simulation environment passes the accuracy test and therefore can be employed in further research.

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REFERENCES

[6] BRAN TS 101 475 v1.2.2 BRAN; HIPERLAN Type 2; Physical (PHY) layer,

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