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A Simulation Model of the Radio Frequency MIMO-OFDM System

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***Abstract*—The paper presents a simulation model of the radio frequency MIMO-OFDM system. The simulation model was made in Matlab Simulink environment. It contains the transmitter, the receiver and the telecommunication channel models. The telecommunication channel model consists of models used during development of technical documentation of IEEE 802.11n. Signals generated at the transmitter output are fully compatible with signals described in IEEE 802.11n [1]. Simulations are conducted on a radio frequency, so they can be compared with results of measurements of real systems.**

***Keywords*—MIMO-OFDM, Simulink, simulator.**

I. INTRODUCTION

THE beginning of the twenty-first century is facing a sign of the development of local wireless networks. Now it can be said, that there is a time of information society. People want to be connected everywhere and all the time. This is the reason of giant popularity of wireless local area networks (WLAN).

Nowadays everybody can buy the access point and create their own wireless network. Devices are cheap and easy to configure. After unpacking from the box newly purchased device is ready to use – just plug and play. They don't need advanced configuration. The market is dominated by devices constructed in accordance with the technical documentation IEEE 802.11g [2]. These devices provide 54Mbps transmission bit rate and so called goodput ca. 30Mbps, but this is no longer enough for the demanding user. Requirements for throughput and reliability of the wireless networks are still growing. Consequently, manufacturers of equipment were started to produce devices in accordance with the recommendation IEEE 802.11n [1]. Equipment supporting this specification offers significantly faster data transfer (theoretically up to 640Mbps) and greater range. These systems, in addition to the multiplexing OFDM (Orthogonal Frequency-Division Multiplexing) use MIMO (Multiple Input, Multiple Output) technology. Thanks to MIMO the transmission takes place between multiple transmitting and receiving antennas. Both, older and newer networks operate in the 2.4 GHz ISM band. This may cause the compatibility problems. The cooperation of these networks in the same area was subject of preliminary studies and very interesting results of this work have been already published [3]. In most cases competition for system transmission resources is won by networks compatible with IEEE 802.11n.

Compatibility problems observed during the experiments are good starting point for further research. For more detailed analysis of this phenomenon it is necessary to control all elements of the telecommunication system. The system simulator, which was implemented in Matlab Simulink environment, allows to have full control. It consists of the transmitter, the receiver and the model of the propagation channel. Environmental influence on propagation conditions is considered on a radio frequency (RF), when most of available simulators (described in literature) work in baseband. In the model a baseband signal is up converted to the radio frequency and then processed with the use of RF channel model. Detection and synchronization in the receiver model is being done in the RF band too. Simulation results can be used during development of new version of the technical documentation of wireless networks.

II. MIMO TECHNIQUE

Devices, which are using MIMO-OFDM technique, consistent with the technical documentation IEEE 802.11n, use up to four antennas at the transmitter and the receiver side. MIMO technology combines advantages of using the well-known SIMO (Single Input Multiple Output) and MISO (Multiple Input Single Output) systems. In a classical SIMO system signal transmitted by one antenna is received by several antennas, which are spaced to ensure no correlation between received signals. The improvement of qualitative parameters of the connection during the interpretation of received signals is achieved by using the data processing algorithms. In MISO systems, we have to deal with the reverse situation, where the same signal is transmitted via several antennas and received by one antenna. MIMO technology combines the features of these two solutions. By using MIMO it is possible to increase the range or the throughput or both of them with some limitation. Of course, there are no obstacles and restrictions to increase the number of antennas.

To understand how this technology works, consider a system with two transmitting antennas and two receiving antennas (Fig.1).

It must be assumed that a channel is constant during the transmission and their transmittance does not change. The received signal can be defined as:

$$\hat{y_1} = \hat{h_{11}} \cdot \hat{x_1} + \hat{h_{12}} \cdot \hat{x_2} + w_1,$$

$$\hat{y_2} = \hat{h_{21}} \cdot \hat{x_1} + \hat{h_{22}} \cdot \hat{x_2} + w_2 \qquad (1)$$

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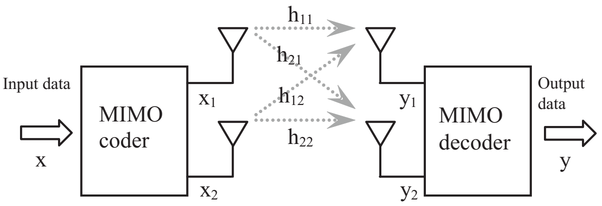

Fig. 1. MIMO system with two transmitting and two receiving antennas (2,2).

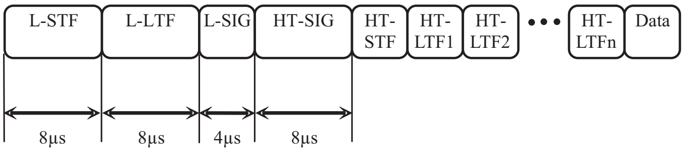

Fig. 2. Time boundaries in simulation model in "mixed mode".

where x denotes the transmitted signal, y received signal and w white Gaussian noise.

In matrix notation eq. 1 can be written as:

$$\hat{Y} = \hat{H} \cdot \hat{X} + W. \tag{2}$$

Matrix H is defined as:

$$\hat{H} = \begin{bmatrix} \hat{h}_{11} & \hat{h}_{12} \\ \hat{h}_{21} & \hat{h}_{22} \end{bmatrix} \tag{3}$$

Equation (3) can be considered as system of two equations with two unknowns. This system has unambiguous solution if there is no correlation between elements of matrix H. Transmitted signals between the transmitter and the receiver can be refracted, diffracted and reflected many of times. The signals received by different antennas, are different. If are not correlated to each other, it can be say that there exist two independent radio channels between the end points of transmission. The transmission speed can increase up to two times. As was previously mentioned in the system might be more than two antennas. So, if the condition of orthogonality is met, then exist independent paths between the transmitter and the receiver and the system can work faster.

III. TIMING BOUNDARIES

Presented model of MIMO-OFDM system operates in "mixed mode". This means that a sequence of symbols transmitted in the preamble is compatible with the format described in the recommendation IEEE 802.11g. Timing boundaries in "mixed mode" for various fields are presented in Fig. 2.

Simulator, as well as IEEE 802.11n devices, is able to transmit data using a bandwidth of 20 or 40MHz. The duration of each OFDM symbol at the transmitter output is 4μs. The first three fields (L-STF, L-LTF and L-SIG) must be properly received by an older and newer devices and are exactly the same as in IEEE 802.11g. L-STF field is used to detect arrival of the first packet from the transmitter, to automatic gain control in the receiver, to the frequency shift estimation and to determine the time dependence between received symbols. This field consists the 10 short training symbols, duration each of them is $0{,}8\mu$s. The whole short training sequence is transmitted using two OFDM symbols of a total duration equal 8μs. L-LTF field contains two long training symbols, which are used to estimate the channel's impulse response. As in the case of L-STF, their total duration is 8μs. The estimation is possible by simple operation of dividing because this sequence is known on the receiving side. The obtained value of impulse response is used to correct the impact of the channel on the SIGNAL field. SIGNAL field contains information about a current transmission, such as transmission bit rate, bandwidth or data field length. Data transmitted in this field is mapped using BPSK modulation and $\frac{1}{2}$ convolution encoder to maximize probability of their correct decoding at the receiver. Other fields HT-SIG, HT-STF, HT-LTF1, HT-LTF2 are equivalent to the previously described fields, but they are only used by devices compatible with the technical documentation IEEE 802.11n. Data field delivers the user information.

In Fig.2:
L-STF – non-HT short training field,
L-LTF – non-HT long training field,
L-SIG – non-HT SIGNAL field,
HT-SIG – high throughput SIGNAL field,
HT-STF – high throughput short training field,
HT-LTF1 and HT-LTF2 – high throughput long training field,
Data – data to transmission.

IV. TRANSMITTER MODEL

Transmitter model has been implemented in Matlab Simulink environment due to the large number of available libraries, which contains function blocks of telecommunication systems, such as modulators, encoders, etc. During developing of model, it appeared that the set of these blocks is insufficient, therefore a lot of additional function blocks were created. Generation method of preamble fields is presented in Figure 3.

The procedure begins with the adding zeros to the training sequence or SIGNAL field in case of its generating. The next four steps (shaded block in Figure 3) are executed only if the SIGNAL field is generated. Convolution encoder is designed to protect data against errors during transmission. In the case

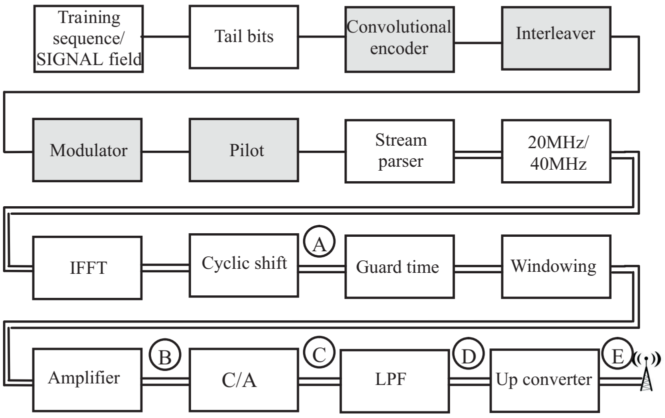

Fig. 3. The transmitter model block diagram (fields compatible with IEEE 802.11g).

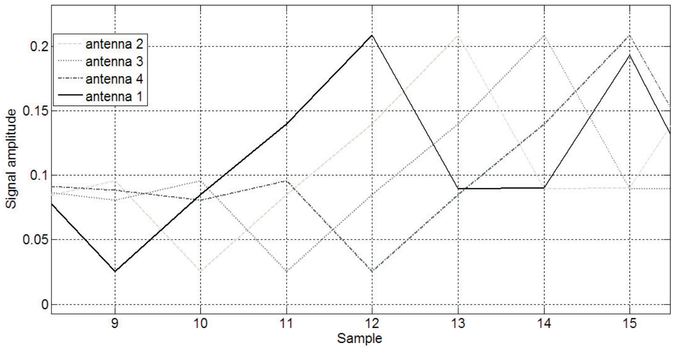

Fig. 4. Time representation of SIGNAL field after CDD operation (amplitudes in relative terms).

of generating the header fields the $\frac{1}{2}$ encoder is selected. After then the data is mapped using BPSK modulator and next the pilot signals are inserted. This type of the modulator was chosen to maximize the probability of correct detection at the receiver. Further steps are common to the generation of training sequence and SIGNAL field. Depending on the required number of spatial streams, independent signals are generated and later are processed in parallel. Since that time each of them is processed separately and at the end will be transmitted from different antenna. In case of operation with 40MHz bandwidth, data are duplicated and inverted in phase by 90 degrees. The next stage of signal processing is to compute the inverse fast Fourier transform IFFT of length equal 64 (20MHz bandwidth) or 128 (40MHz bandwidth). In the result the signal is in the time domain.

Independent signals at the output of IFFT block are cyclically shifted using the CDD technique (Cyclic Delay Diversity) [4]. Signals transmitted from multiple antennas are cyclically shifted to each other by a certain, strictly defined value. For example, for four transmitting antennas, the signal from the first antenna is not shifted, from the second antenna is shifted by 50ns (1 sample of OFDM symbol in case of bandwidth of 20MHz), the third of 100ns, and for the fourth 150ns. SIGNAL field scrap (signal at point A in Figure 3) is shown in Figure 4.

The CDD increases the frequency selectivity of the channel and eliminates unintentional and undesirable antennas beamforming effects. For the IEEE 802.11g receiver with single antenna, the received signal coming from multiple transmitting antennas is a convolved signal transmitted through a channel with a delayed response. It is assumed, that for older devices cyclic shift up to 200ns is tolerated. Cyclic shift can not be bigger than guard time, which is added to each OFDM symbol (800ns for IEEE 802.11g, n). Guard time protects the transmission from interference. Then the signal is windowed to ensure a smooth transition between consecutive OFDM symbols. Finally, signal is directed to the amplifier, where its amplitude is set and OFDM symbol is ready to up converting. Figure 5 presents signals in points B, C and D of the transmission block diagram (Figure 3).

At point B each OFDM symbol is represented by 80 samples (for bandwidth of 20MHz) or 160 samples (for bandwidth of 40MHz). The next step is to convert the signal to rectangular

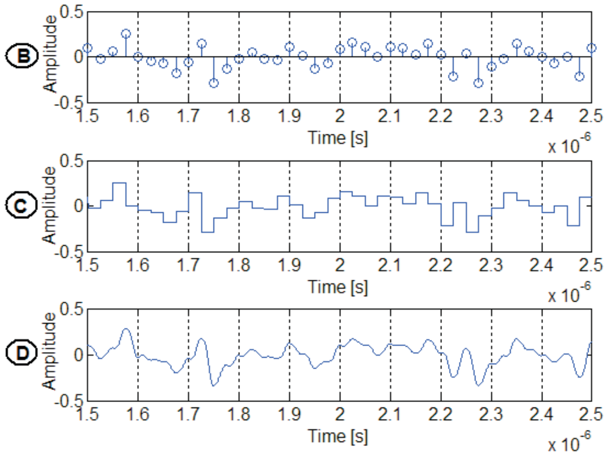

Fig. 5. Time representation of signal in simulator in points marked in Figure 3 (amplitudes in relative terms).

signal (middle graph in Figure 5). Then the signal is filtered using fifth degree Butterworth filter with 0.5 cutoff frequency. The analog signal is obtained at the filter output (bottom graph in Figure 5), which is transmitted in RF band after multiplication by a carrier frequency.

OFDM symbols, that contain user data are created in a different way than the symbols described earlier. Block diagram describing this process is illustrated in Figure 6. In this case the data are not backwards compatible.

Block 'data', which is responsible for generating user information was built based on the Bernoulli generator with probability of zero equal to 0.5. A service field is added to the data from the generator output, which is used to initialize the scrambler. Convolution encoder of effectiveness 1/2, 2/3, 3/4 or 5/6, depending on the transmission rate, is designed to protect data during transmission.

So, prepared data stream is distributed to individual streams and each of them is interleaved. Depending on the transmission rate, BPSK, QPSK, 16-QAM or 64-QAM modulator is used. In the next step pilot signals are inserted in the corresponding subcarriers, inverse fast Fourier transform IFFT is calculated and cyclic prefix is added to each symbol. Further steps are similar to those, performed during the generation of header fields. The spectrum of the OFDM symbol at the transmitter

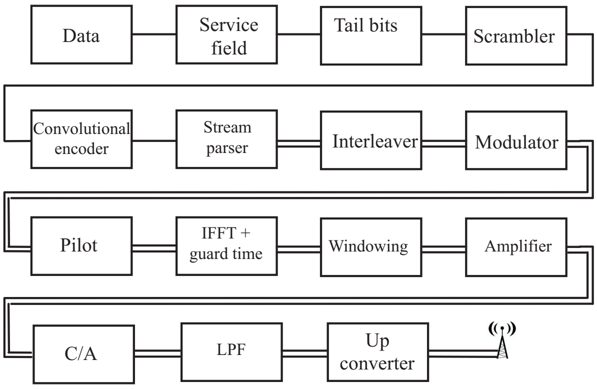

Fig. 6. Block diagram of the transmitter (user data only).

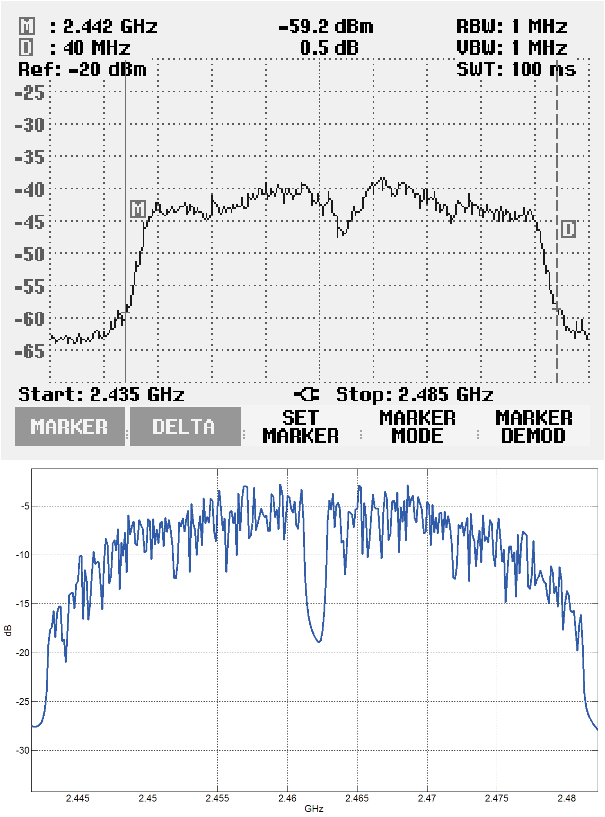

Fig. 7. The comparison of the signal spectrum at the output of the real transmitter and at the output of transmitter model (40MHz bandwidth).

output is shown in Figure 7.

V. PROPAGATION CHANNEL MODEL

A set of different types of channels, that have been used during the development of technical documentation of IEEE 802.11n, were implemented in the simulator. This set consists of models of 6 channels identified by the letters from A to F [5]. Each of them has different number of clusters and delays. The simples one (Channel A) take into account only one cluster, more complicated two or more clusters (Channels B to F). Models B, D and E were largely used to compare proposal during the development of IEEE 802.11n as outlined in [6]. The channel impulse response of channel B and F is presented respectively in Figure 8 and Figure 9.

The vertical bars indicate a delayed response. It can be noticed that cluster are overlapping. The delayed response in overlapped clusters is a composite of the power from this clusters. The taps powers from overlapping clusters are added at each delay.

For each type of channel it is possible to set the distance between the antennas at the transmitter and receiver, which shall be used during designated correlation matrices.

Path loss was added to the model of the channel to make possibility of determining the maximum range and system throughput in simulations. Simple propagation model [5] was used:

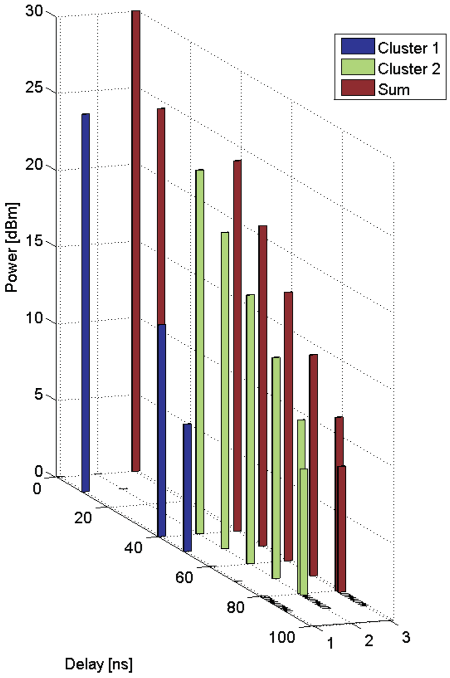

Fig. 8. Impulse response of channel type B.

$$L(d) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5, \quad d \le d_{BP}$$

$$L(d) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5 + \\ +35\log_{10}\left(\frac{d}{d_{BP}}\right), \quad d > d_{BP} \tag{4}$$

where:

d – the separation distance between the transmitter and receiver in meters,

f – signal frequency in Hz,

d_{BP} – the breakpoint distance in meters,

SF – the shadow fading loss in dB.

The breakpoint can be defined as:

$$d_{BP} = \frac{4\pi h_{Tx} h_{Rx}}{\lambda} \tag{5}$$

where:

h_{Tx} – transmitter high in meters,

h_{Rx} – receiver high in meters.

In the path loss model the shadow fading also can be include. Then the equation (1) is given as follows:

$$L(d) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5 + SF, \quad d \le d_{BP}$$

$$L(d) = 20\log_{10}(d) + 20\log_{10}(f) - 147.5 + \\ +35\log_{10}\left(\frac{d}{d_{BP}}\right) + SF, \quad d > d_{BP} \tag{6}$$

Path loss between a transmitter and a receiver at a distance 300m and frequency of 2.432GHz (fifth channel) for channel models from A to F was shown in Figure 10.

The shadow fading loss is modeled by a log-normal distribution (Gaussian in dB) with zero mean. Independent signals from transmitting antennas are directed to the input of the model of radio channel. The same number of signals from the

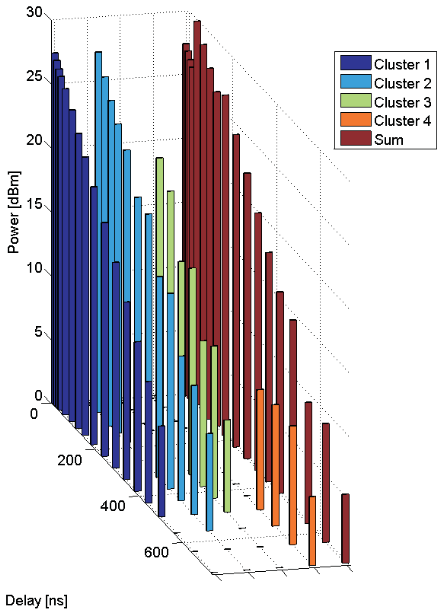

Fig. 9. Impulse response of channel type F.

channel model output is received by antennas in the receiver. For 4×4 system the transmittance matrix of channel have 16 values.

VI. RECEIVER MODEL

The receiver model is fully automatic and it is able to detect the beginning of the transmission and to perform full synchronization. Block diagram of the receiver is presented in Figure 11.

The first step, performed in the receiver, is detection of arrival of the packet, which takes place on radio frequency. For this task receiver use all antennas and in case of preamble receiving Maximum Ratio Combining algorithm is used. In case of data portion independent streams are received by all antennas. In receiver model a correlation algorithm based on the 10 short training symbols transmitted at the beginning of each transmission was used. At this stage the receiver is able to determine whether the transmission takes place using the bandwidth of 20 or 40MHz. After correct detection the data signal is down converted to the baseband. Of course the most important thing is precise synchronization, which a synchronization block is responsible for. The main task of this block is detecting of the beginning of a long training sequence. It is done in the receiver by using correlation algorithm. Example of the results obtained after rendering this algorithm is shown in Figure 12.

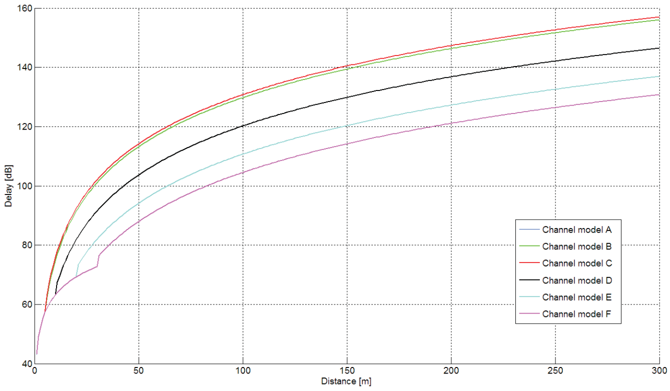

Fig. 10. Path loss between transmitter and receiver ($d = 300$m, $f = 2.432$GHz.

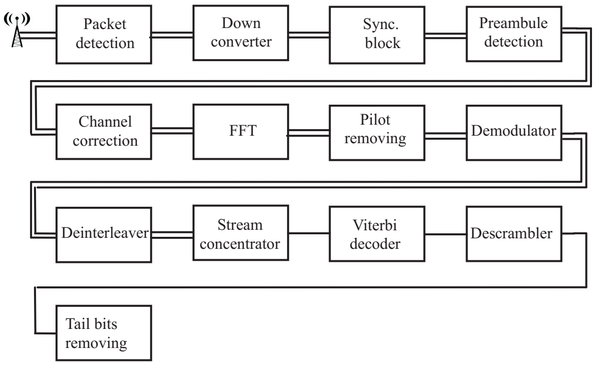

Fig. 11. Block diagram of the IEEE 802.11n receiver model.

In the presented case the algorithm have no problem with identifying the start of transmission of the long training sequence (autocorrelation reached a value close to one). The synchronization block is also reliable for making the channel estimation. The receiver has knowledge about the training sequence, which was transmitted and it can make the channel estimation. First estimation is done for data sent in the header, and the second one for the user data. First operation is simple and does not require large computing power – receiver divides the received signal by a known training sequence. For the second estimation it is necessary to solve the equations. In case of four transmit and four receiving antennas the system of equations is composed of sixteen equations with sixteen unknowns. The preamble detection block validates propriety of header reception by calculating the CRC. Additionally in this block the acquisition information about transmission, such as the number of spatial streams, the modulator type, type of convolution encoder, bandwidth, data field length, etc is done. The data at the output of synchronization block are used to correct the influence of the propagation channel. After signal correction, the Fast Fourier Transform of length 64 (bandwidth of 20MHz) or 128 (bandwidth of 40MHz) is performed. In the

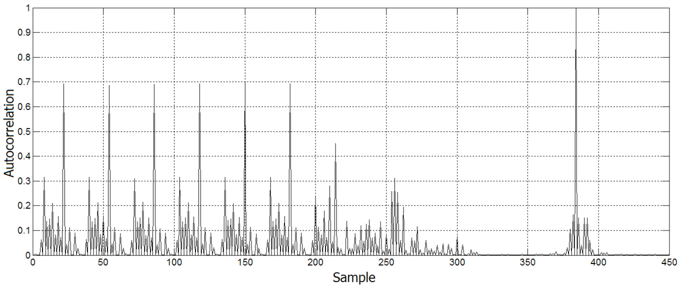

Fig. 12. Output of the autocorrelation algorithm (during long training field detection).

next step pilot subcarriers are removed from signal and data is routed to the demodulator block, which is set in accordance to information extracted from a received preamble. Then the data are deinterleaved and one output stream is created (in case of multi-stream transmission in concentrator block). The signal from concentrator is delivered to the Viterbi decoder, and later to the descrambler. The last operation is removing the tail bits which have been added in the transmitter.

The receiver measures a lot of transmission parameters etc. the SNR (Signal to Noise Ratio), the interference level, the BER (Bit Error Ratio) and noise level. Based on all available information, a receiver changes a transmission rate.

VII. SUMMARY

Presented in this paper simulation model of the MIMO-OFDM system is able to perform simulations with data rates from 6.5 to 540Mbps. Simulation time depends on the performance of the computer, which is carried out on. The number of antennas at the transmitter and receiver can be chosen form one two four. Model can be used to examine the impact of modification of various system parameters on the quality of transmission. The structure and format of the transmitted data are consistent with the technical documentation for IEEE 802.11n.

The undoubted advantage of the presented solution is that the simulations will be carried out on radio frequency. Thus, simulation results could be directly related to measurements of real systems. The advanced parameters of simulation model can be change to achieve convergence of the simulation results to results of real system tests. In next step the simulator can be used to predict coverage and performance of wireless networks in different environments. Simulator can be also utilized to verify certain technical solutions in the future wireless networks proposals.

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