

Performance Analysis of PCFICH and PDCCH LTE Control Channels

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Abstract. *Control channels are the most important part of a physical layer in mobile communication systems. The motivation for our paper is to evaluate the performance of control channel implementation in the Long Term Evolution (LTE) system. The paper covers simulation of the complete signal processing chain for the Physical Control Format Indicator Channel (PCFICH) and Physical Downlink Control Channel (PDCCH) in the LTE system, Release 8. We have implemented a complete signal processing chain for downlink control physical channel models. These channel models are an extension of the existing MATLAB LTE downlink simulator. The paper presents results of the PCFICH and PDCCH control channel computer performance analysis in various channel conditions.*

Keywords

Long Term Evolution, Release 8, control channels, traffic channels, Physical Control Format Indicator Channel, Physical Downlink Control Channel, MATLAB, link level simulator.

1. Introduction

The next evolutionary step in high data-rate packet mobile systems is the 3GPP Long Term Evolution (LTE). LTE still belongs to the third generation of mobile systems. It directly follows up on the UMTS and HSPA systems. LTE supports variable bandwidths ranging from 1.4 MHz to 20 MHz. The Round-trip time is less than 10 ms [1]. Theoretical peak data rate in downlink is 172.8 Mbps [2].

Link level simulators are typically focused on the performance analysis of traffic channels. For an overall system performance and comparison with real network deployment it is necessary to include control channels in the simulations. Control channels are typically designed with a more robust forward error correction and modulation than traffic channels. In the case of the 3GPP LTE system, the Orthogonal Frequency-Division Multiple Access (OFDMA) method and robust scrambling of control channel information are used [3–5].

The physical layer of LTE in the downlink direction includes three types of traffic channels, Physical Downlink Shared Channel (PDSCH), Physical Multicast Channel (PMCH), Physical Broadcast Channel (PBCH), and a trio of control channels – Physical Control Format Indicator Channel (PCFICH), Physical Hybrid-ARQ Channel (PHICH) and Physical Downlink Control Channel (PDCCH) [6]. Not all physical control channels are used to transfer information from higher layers of the LTE system. They are not associated with transport channels. This article is focused on signal processing and bit error rate (BER) analysis in the PCFICH and PDCCH channels. The functioning of these two control channels is very closely related and the ability to decode PDCCH control data is dependent on both of these channels.

Performance analysis of the LTE system is usually presented for traffic channels [7]. The performance analysis of control channels is mentioned in [8] in a theoretical base only. Article [9] examines a similar problem which presents Physical Downlink Control Channel performance analysis results in an AWGN channel model. However, a complete computer performance analysis of LTE physical control channels in fading channel models is missing. Our motivation is to implement control channels as an extension of the MATLAB LTE downlink simulator developed by Vienna University of Technology [10].

The paper is organized as follows. First the LTE physical layer and control channels are described. The next part brings a detailed description of the signal processing chain of surveyed control channels. Simulation of control channels and their results are mentioned in the third part and summarized in the conclusion.

2. LTE Downlink Physical Layer

The physical layer of LTE in the downlink direction is based on the OFDMA modulation and access scheme. OFDMA is a multi-user version of a basic OFDM modulation scheme. Multiple access is provided by assigning subsets of subcarriers to individual users or physical channels.

The base LTE downlink physical layer transceiver (transmitter-receiver) model is shown in Fig. 1. White col-

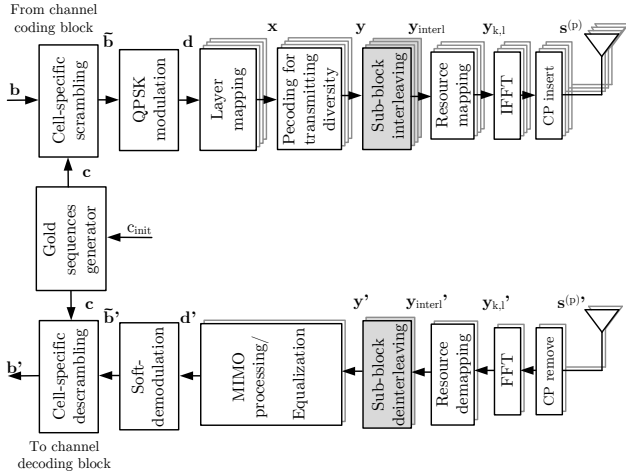


Fig. 1. A common PCFICH and PDCCH transceiver signal processing chain.

ored blocks in the signal processing chain are common for PCFICH and PDCCH control channels. The Sub-block interleaving and deinterleaving blocks (gray colored) are used only in the PDCCH signal processing chain. The PCFICH and PDCCH channel coding and decoding blocks are described in detail in a special subsection.

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The codeword \mathbf{b} from the channel coding block is scrambled with a scrambling sequence which is unique for each cell of the system. Scrambling sequences are pseudo-random sequences created by the generator of Gold sequences [3]. At the beginning of every subframe the generator is initialized using the slot number in the radio frame n_s and the cell identification number N_{ID}^{cell} . In the case of the PCFICH, the Gold sequences generator is initialized according to the equation

$$c_{init} = \left\lfloor \frac{n_s}{2} \right\rfloor \times (2N_{ID}^{cell} + 1) \times 2 + N_{ID}^{cell}. \quad (1)$$

In the case of the PDCCH channel, the Gold sequences generator is initialized according to

$$c_{init} = \left\lfloor \frac{n_s}{2} \right\rfloor \times 2^9 + N_{ID}^{cell}. \quad (2)$$

The process for scrambling is performed as

$$\bar{b}(i) = b(i) \oplus c(i) \quad (3)$$

where $\bar{\mathbf{b}} = \bar{b}(i), \bar{b}(i+1), \dots, \bar{b}(M_{bit}^b - 1)$ is the scrambled codeword, $\mathbf{b} = b(i), b(i+1), \dots, b(M_{bit}^b - 1)$ is the input codeword, $\mathbf{c} = c(i), c(i+1), \dots, c(M_{bit}^b - 1)$ is the pseudo-random sequence \mathbf{c} , M_{bit}^b is the length of the input sequence

\mathbf{b} in bits and $i = 0, 1, \dots, M_{bit}^b - 1$. The scrambled bits $\bar{\mathbf{b}}$ are modulated by QPSK modulation and then form a block of complex-value symbols denoted as \mathbf{d} .

The vector of modulated and scrambled symbols \mathbf{d} is then mapped into v -layers $x^{(0)}(i), \dots, x^{(v-1)}(i)$, depending on the number of transmitting antennas, where $v = \{1, 2, 4\}$. In the case of one transmitting antenna, layer mapping is not used, thus $x^{(0)}(i) = d^{(0)}(i)$. In the case of two or four transmitting antennas, layer mapping and symbol selection are provided sequentially [3]. In the case of one transmitting antenna, transmit precoding is not provided. In the case of two or four transmitting antennas, it is necessary to provide precoding for transmit diversity using a Space-frequency diversity block code (SFBC). The scheme for the event of two transmitting antennas is shown in Fig. 2. The scheme for the event of four transmitting antennas is shown in Fig. 3.

Complex symbols for each transmit antenna are grouped into quaternary symbols, so-called symbol quadruplets, which are mapped to defined positions in the resource grid in the Resource mapping block. Furthermore, the IFFT operation with symbols in the resource grid is performed, the cyclic prefix (CP) is inserted and these operations form the time-continuous signal $\mathbf{s}^{(p)}$ [3]. Here, p denotes an antenna port.

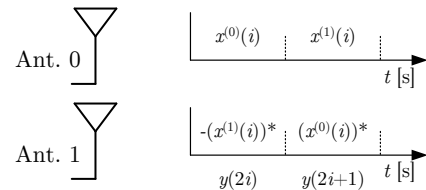


Fig. 2. A precoding scheme for transmit diversity (2 Tx antennas).

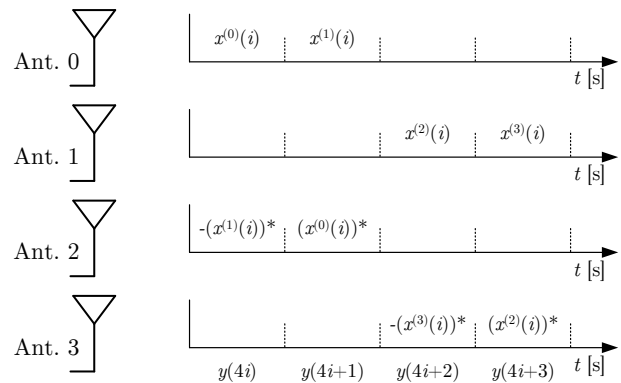


Fig. 3. A precoding scheme for transmit diversity (4 Tx antennas).

After the time-continuous signal $\mathbf{s}^{(p)}$ passes through the channel, which is described by the matrix of channel coefficients \mathbf{H} , the CP is removed and FFT is performed. In a resource demapping block, PCFICH and PDCCH received symbols are selected. In this block, estimated and inverted channel coefficients \mathbf{H}^{-1} , which correspond to PCFICH and PDCCH symbols, are also selected. In the case of using more than one transmitting antenna, MIMO detection is provided [11]. Complex-valued symbols are equalized and

soft-demodulated (Soft-sphere decoder). Demodulated bits \mathbf{d}' lead to the Cell-specific descrambling block, where the descrambling process is provided using the equation

$$b(i) = \bar{b}(i) \oplus c(i) \tag{4}$$

where $\mathbf{c} = c(i), c(i+1), \dots, c(M_{\text{bit}}^{\mathbf{b}} - 1)$ is the same pseudo-random sequence as was used at the transmitting side. The output of the Cell-specific descrambling block \mathbf{b}' leads to the PCFICH or PDCCH channel decoding block. Note, that \mathbf{d} is a vector of complex-valued modulated symbols and \mathbf{d}' is a vector of demodulated bits.

In the PDCCH signal processing chain, Sub-block interleaving is used. Complex-valued symbols \mathbf{d} are mapped and precoded into v -parallel streams and mapped to the quadruplets of symbols (quadruplet is quaternion of symbols). The quadruplets in each stream are interleaved using the free-quadratic permutation polynomial (QPP) technology [3, 12]. Deinterleaving is performed with received symbols and also with the corresponding matrix of the estimated and inverted channel coefficients \mathbf{H}^{-1} . The modified symbols and channel coefficients are led into the MIMO detector and soft-demodulator and results to a vector of demodulated bits \mathbf{d}' .

2.1 Physical Control Format Indicator Channel

Via the PCFICH channel, the Control Format Indicator (CFI) is transmitted. The value stored in CFI determines the number of resource elements in the resource grid (in the time domain) carrying the PDCCH control channel data. It determines the PDCCH control area in each subframe in downlink. PCFICH is transmitted in the first OFDM symbol in a subframe [3]. The CFI parameter takes only the values 1, 2, or 3. The value CFI = 4 is reserved. For a bandwidth greater than 1.4 MHz, which is defined by more than 10 Resource Blocks (RB) [4], the number of OFDM symbols used for transmitting control information is the same as the value stored in CFI. Otherwise the value is CFI + 1.

CFI	CFI codeword $\mathbf{b} = [b_0, b_1, \dots, b_{31}]$
1	[01101101101101101101101101101101]
2	[10110110110110110110110110110110]
3	[11011011011011011011011011011011]
4 (reserved)	[00000000000000000000000000000000]

Tab. 1. PCFICH Channel Coding.

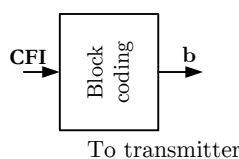


Fig. 4. PCFICH channel coding signal processing chain.

A block diagram of the PCFICH channel coding signal processing chain [13] is shown in Fig. 4. A bit sequence \mathbf{b} of 32 bits in length is assigned to CFI bit value of two bits in length, according to Tab. 1. Code rate of the PCFICH block code is $R_{\text{CFI}} = \frac{1}{16}$. The channel coded bit vector \mathbf{b} leads to the transceiver block.

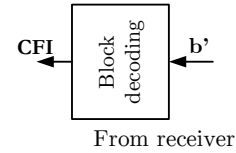


Fig. 5. PCFICH channel decoding signal processing chain.

After the signal passes through the transceiver signal processing chain, the received and channel coded bit vector \mathbf{b}' leads to the channel decoding block which is shown in Fig. 5. In this block the input codeword of 32 bits in length is compared with codewords mentioned in Tab. 1 and the received CFI value is obtained.

2.2 Physical Downlink Control Channel

The PDCCH is the most important control channel in downlink. It supports signalling for data channels in downlink and uplink [14, 15]. Via this channel, Downlink Control Information (DCI) is transmitted. DCI contains the information about resource scheduling for downlink and uplink, transmit power commands (TPC), etc. The block diagram of PDCCH channel coding signal processing chain [13] is shown in Fig. 6. Individual DCI messages of different formats are channel coded. Cyclic redundancy check (CRC-16) of 16 bits in length is added to the DCI message [4]. Afterwards, the CRC is scrambled with the binary value of the Radio Network Temporary Identifier (RNTI) and the antenna mask if necessary. The next block in the channel coding processing chain is a convolutional coder with the coding rate $R_{\text{DCI}} = \frac{1}{3}$. In the rate matching block, interleaving and length reduction of the encoded DCI message are performed [3]. The interleaving depth J is defined by the relation

$$J = \left\lceil \frac{l_{\text{IN}}}{32} \right\rceil \tag{5}$$

where l_{IN} is the length of input message in bits.

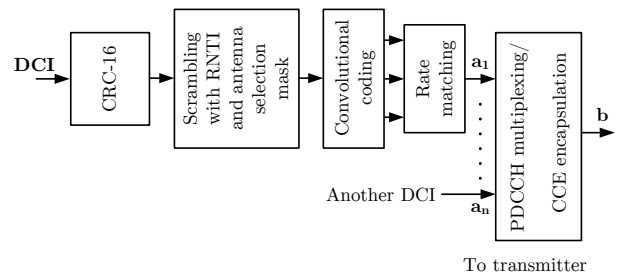


Fig. 6. PDCCH channel coding signal processing chain.

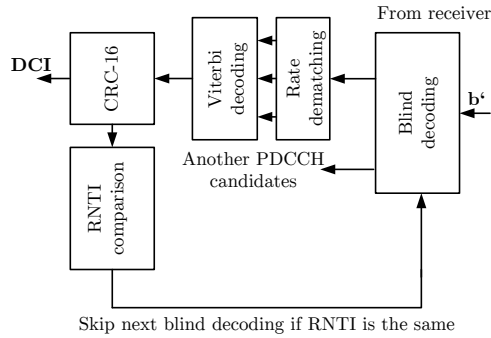


Fig. 7. PDCCH channel decoding signal processing chain.

The above described operations with all DCI messages are provided in parallel and these messages come into a PDCCH multiplexing block. The coded DCI messages $\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_n$ (n denotes number of DCI's) are encapsulated into Control Channel Elements (CCE). These elements are mapped into individual PDCCH formats according to their bit length, see Tab. 2. This procedure is necessary because the blind decoding technology is used on the receiving side. Unused CCE space in the individual PDCCH is filled with $\langle \text{NIL} \rangle$ elements and a vector of channel coded bits \mathbf{b} is formed and led to the transceiver block [4]. The PDCCH's are arranged subsequently into a PDCCH frame.

PDCCH format	Number of CCEs	Number of REGs	Number of PDCCH bits
0	1	9	72
1	2	18	144
2	4	36	288
3	8	72	576

Tab. 2. Supported PDCCH formats.

The output of the transceiver block leads to the PDCCH channel decoding block which is shown in Fig. 7. In the blind decoding block, the vector of input bits \mathbf{b}' is scanned according to the known lengths of the PDCCH formats. The output of the blind decoding block is up to 44 so-called PDCCH candidates. Each of these candidates enters sequentially into blocks implementing channel decoding, i.e. rate dematching and Viterbi decoding. From these decoded bits a new cyclic redundancy check is computed (CRC-16) and modulo 2 added to the cyclic redundancy check, which has been received and we get a new value of RNTI' . In the event that both CRC's are the same, the RNTI value known to the system and the new RNTI' are identical and we have the DCI format sought. Further blind decoding of the examined PDCCH is discontinued and the next PDCCH enters the blind decoding block.

3. Simulations

As mentioned above, the Link level simulator is used as a base physical layer model of LTE. The simulator was

developed at the Vienna University of Technology [10]. The model was extended by adding control channels. A performance analysis was made by way of analyzing the BER of PCFICH and PDCCH and the results are presented in this section. Tab. 3 lists the main parameters of the simulation system.

Parameters	Description
Frame structure	FDD
System bandwidth	1.4 MHz
Antenna configuration $[N_{\text{TX}} \times N_{\text{RX}}]$	$1 \times 1, 2 \times 1, 4 \times 2$
Cyclic prefix	Normal
Channel estimation method	Perfect
Receive algorithm	Soft-sphere decoder
Channel fading type	Block fading
Channel models	AWGN
	Pedestrian B
	Vehicular A
	Typical Urban Rural Area

Tab. 3. Control channels simulation parameters.

The simulator works only with the FDD frame structure. The number of transmitted subframes was 10000 for PCFICH and 2000 for PDCCH. This difference is due to the length of the CFI and DCI input message in order to achieve a BER of at least 10^{-4} . Due to a system bandwidth of 1.4 MHz, there were 6 RBs. The cyclic prefix of normal duration and the Soft-sphere receiver algorithm were used. The used channel models [16] are listed in Tab. 3. The BER simulation results for the PCFICH and PDCCH control channels are presented in dependence on the type of antenna configuration [11].

3.1 Performance Analysis of the PCFICH

The results of the PCFICH control channel transmission simulation and subsequent analysis of BER in dependence on the Signal-to-Noise Ratio (SNR) for all antenna configurations and models of the transmission channels used are listed in this section. The BER is calculated from the difference between two-bit CFI values obtained at the beginning and at the end of the transmission chain. The PCFICH BER curves arranged according to the available antenna configurations are shown in Figs. 8 to 10.

Antenna configuration $[N_{\text{TX}} \times N_{\text{RX}}]$	Minimal SNR value in dB for different channel type				
	AWGN	Ped B	Veh A	TU	RA
1×1	0.8	9.3	11.7	8.5	16.3
2×1	1.0	5.6	5.4	4.6	8.4
4×2	-2.4	-1.2	-0.7	-1.0	-0.5

Tab. 4. Comparison of the simulation results of minimal SNR for BER equalling 10^{-4} in the PCFICH channel.

Tab. 4 summarizes results of PCFICH BER. The values of SNR are given at which the BER in the PCFICH channel reaches the reference level of 10^{-4} .

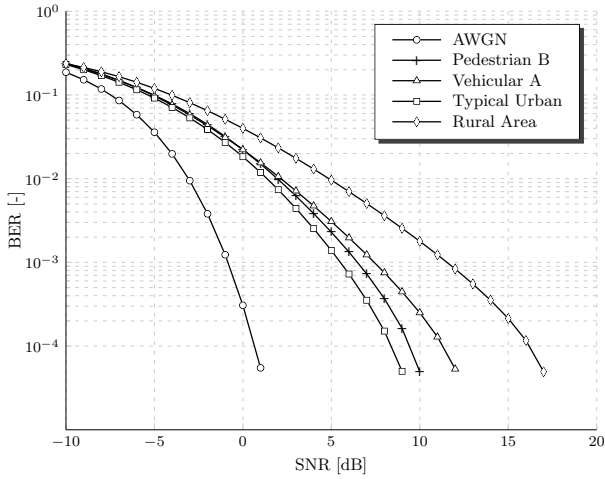


Fig. 8. BER of the PCFICH for 1 transmitting and 1 receiving antenna.

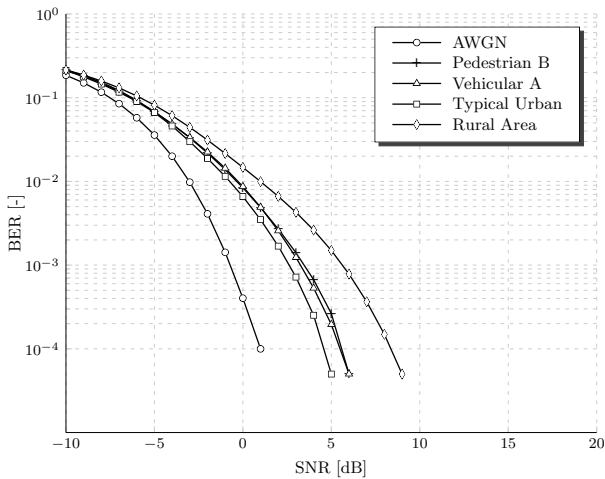


Fig. 9. BER of the PCFICH for 2 transmitting and 1 receiving antenna.

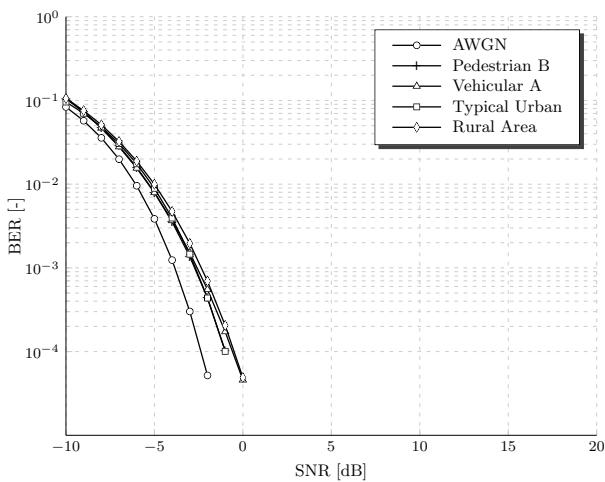


Fig. 10. BER of the PCFICH for 4 transmitting and 2 receiving antennas.

3.2 Performance Analysis of the PDCCH

The results of the PDCCH control channel transmission simulation and subsequent analysis of BER in dependence on the SNR for all antenna configurations and models of transmission channels used are listed in this section. The BER is calculated from the DCI value in bits (format 0 - test case set at the beginning of the simulation for performing the blind decoding faster) at the beginning and at the end of the transmission chain. The PDCCH BER graphs arranged according to the available antenna configurations are shown in Figs. 11 to 13.

Summarized results of PDCCH BER are shown in Tab. 5. The values of SNR are given at which the BER in the PDCCH channel reaches the reference level 10^{-4} .

As can be seen from presented graphs, the PCFICH BER is markedly lower than the PDCCH BER. This is given by the size of the data transmitted and the used channel cod-

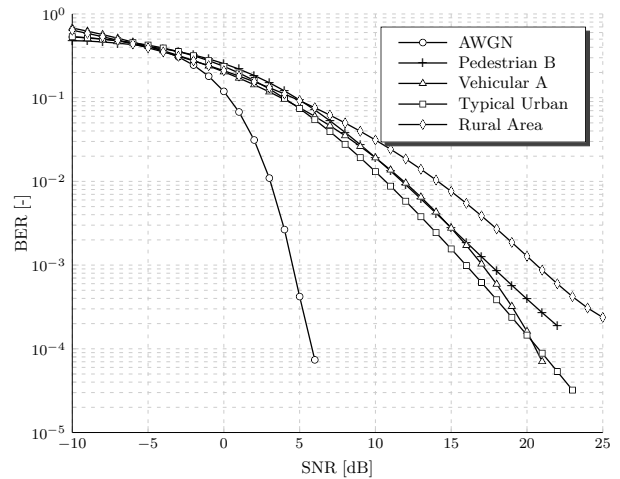


Fig. 11. BER of the PDCCH for 1 transmitting and 1 receiving antenna.

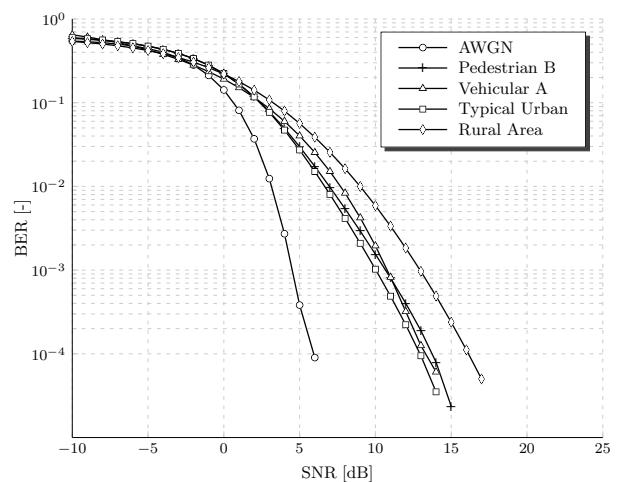


Fig. 12. BER of the PDCCH for 2 transmitting and 1 receiving antenna.

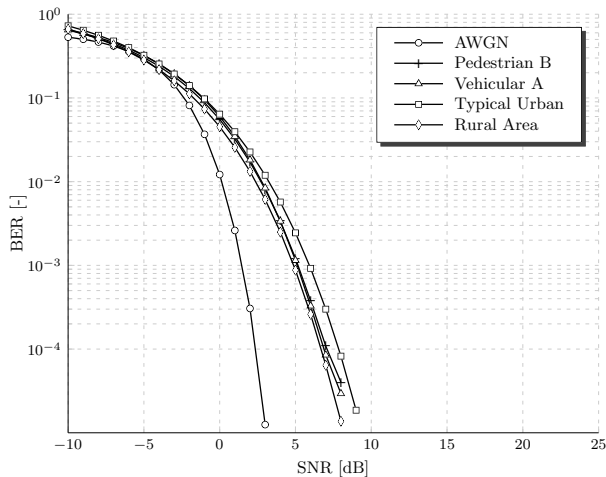


Fig. 13. BER of the PDCCH for 4 transmitting and 2 receiving antennas.

Antenna configuration [$N_{TX} \times N_{RX}$]	Minimal SNR value in dB for different channel type				
	AWGN	Ped B	Veh A	TU	RA
1×1	5.6	24.0	21.0	21.0	27.0
2×1	5.9	13.8	13.8	13.0	16.1
4×2	2.4	7.1	7.0	7.7	6.7

Tab. 5. Comparison of the simulation results of minimal SNR for BER equalling 10^{-4} in the PDCCH channel.

ing. While in the case of the PCFICH channel, where a two-bit CFI codeword is transmitted, in the case of the PDCCH, many more bits are transmitted. All types of possible antenna configurations are usable in investigated channel models. For both physical channels, the use of transmit diversity significantly improves the quality of reception. In the case of PDCCH and 4 transmitting and 2 receiving antennas, for all investigated types of fading channels, PDCCH BER reaches the reference BER level with SNR difference which is lower than 0.5 dB for individual fading channels. In the case of PCFICH and same antenna configuration, for all investigated types of fading channels, PCFICH BER reaches the reference BER level with SNR difference which is lower than 0.8 dB for individual fading channels. This fact assures consistent behavior of the PCFICH and PDCCH control channels and thereby overall LTE system performance. This positive feature illustrates the fact that both investigated control channels are well designed with respect to using most types of transmission environments represented by the used channel models especially with respect to moving objects.

4. Conclusion

The paper was focused on the study of two selected control channels because their functioning is mutually linked together. The PCFICH and PDCCH signal processing models were created in a MATLAB environment and the models were added to the LTE Link level simulator. The performance of these two control channels was analyzed in the

AWGN channel model and in the basic types of fading channels. In further research, simulations with an extended cyclic prefix and larger system bandwidth will be performed. The performance analysis of the PHICH physical channel should also be performed.

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