Error characteristics and their prediction in ZigBee transmission at coexistence conditions

BOHUSLAVEK ZDENEK and MASIK ILJA
Department of Electrical Engineering and Automation , Faculty of Engineering
Czech University of Life Sciences Prague , Kamycka 129
CZECH REPUBLIC
bohuslavek@tf.czu.cz

Abstract: - Currently, the unlicensed ISM band (Industrial Scientific and Medical) 2.4 GHz is become saturated due many standards used at once. In agricultural production has ZigBee a lot of applications, from wireless sensors networks to complicated automation applications. This paper deals with improving the coexistence properties ZigBee (IEEE 802.15.4), while keeping compatibility with the basic standard. This paper describes principles and application of forward error correction above the physical layer, consisting of block data interleaver and Hamming code, and also the effect of improvements in coexistence with variously loaded WiFi 802.11g.

Keywords: - dependability, Hamming, wireless, ZigBee

1 Introduction

Currently, the unlicensed ISM band (Industrial Scientific and Medical) 2.4 GHz become saturated due many standards used at once. Beginning WLAN networks (IEEE 802.11b/g/n), through Personal Area Networks such as Bluetooth or ZigBee (IEEE 802.15.1, 802.15.4) and last but not least, a lot of non-standardized wireless transmi- ssions, such as wireless phones, PC peripherals etc. The coexistence of different wireless networks in the ISM band is inevitable, and it is also very probable that there will be a carrier frequencies overlapping. In agricultural production, as at any other area with people traffic, a lot of interference situations caused by mobile devices hanged by persons can occur. Mobile phones, tablets and etc. are very usual at present time and WiFi or Bluetooth are used very frequently. Method described by this paper, has been built for anemometer data logger units, used for parameters measurement of new type windbreak at Research Institute of Soil and Water Conservation. An anemometer data logger (with ZigBee wireless data download) has been positioned in the field with aim to get long term capabilities of windbreak units. When the data was downloaded, the collection unit has sometimes problems with interference from coexistent standards, caused by the equipment handled by the person who operates the collection unit. Aim of this paper is describe main characteristics for coexistence improvement.

WiFi (802.11)

802.11g is currently being slowly replaced by 802.11n, but is still very frequently used. Theoretical transfer speed of 802.11g is 54 Mbit/s. Channels, their width, spacing and overlapping is identical with 802.11b, but with increased throughput, which is achieved using the OFDM modulation. OFDM (Orthogonal Frequency Division Multiplex) is a method, which allows operation of adjacent channels with overlap, without causing interference. It is a method that allows better utilization of given range, which increases noise immunity against the simple data transmission. Given channel is divided into sub channels and these are used as parallel separate links of communication, of course, with lower throughput. 802.11g allows channel width 22 MHz, divided into 52 subchannels, where 48 are data channels and 4 pilot channels used to synchronize transmission. In order of best band utilization, the channels are defined with an overlap. This overlap is then eliminated by orthogonality of adjacent frequencies. Therefore there no inter-channel interferences occur, because when one channel transmits a particular character, neighboring channels are zero. OFDM actually converts the serial data transmission to parallel information transfer. DSSS (Direct Sequence Spread Spectrum) method uses redundant data to spread information to the spectrum and thereby is increased interference resistance. In practice, bits to transmit are replaced by chip sequences longer than the original data. This causes to data redundancy, which can be used at the receiver side to correct errors resulting from noise in transmission channel. The 802.11g standard allows the use of both OFDM and DSSS modulation. Fig. 1 is a frame structure of 802.11g, where in relation to coexistence between ZigBee and WiFi, is interesting timing. PLCP Preamble sequence is 16 µs long, followed by PLCP Header with 4 µs length independently on current transfer speed, after that follows the data. Timing of data part depends on the speed and coding rate, [1].

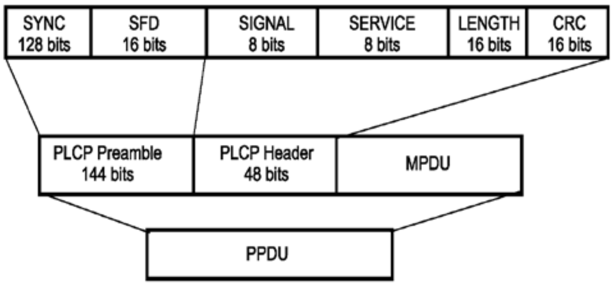

Fig. 1: Frame format of 802.11g, [1]

ZigBee (802.15.4)

ZigBee is commercial wireless technology based on standard IEEE 802.15.4, which, like Bluetooth, belongs to the category of PAN networks. ZigBee can operate in three bands to ensure usability on a global scale. Namely it is band 868 MHz, 915 MHz and 2.4 GHz. Each band has different maximum baud rate, at 868 MHz its 20 kbit.s^{-1}, band 915 MHz 40 kbit.s^{-1} and for 2.4 GHz is the baud rate 250 kbit.s^{-1} [2]. ZigBee physical layer uses in order to increase the reliability of transmission the forward error correction DSSS, where each four bits to send are substituted with sequences of 32 chips. At this stage, the signal is transmitted with O-QPSK modulation, which allows sending four bits per symbol with symbol timing 16 µs. At the receiver, when O-QPSK demodulation is done, microcontroller will for each 32 chip sequence evaluate the probability of compliance with each of the 2^4 variants of 32 chip originals, and then replace with appropriate 4 information bits, based on the best fit. Instead of 4 bits, are transmitted 32, which mean the channel bandwidth is reduced to 1/8. The benefit is the ability to statistically detect and "fix", or rather "ignore" errors caused by noise in the transmission channel. The efficiency of these forward error correction, depends on the choice of chip sequences mainly is important their mutual dissimilarity. That determines the number of bit errors necessary for wrong substitution and consequential error, [3].

2 Materials and Methods

2.1 Experimental hardware & software

In development process was used hardware by Texas Instruments - SmartRF05 that uses SoC CC2530F256. This microcontroller has an integrated RF part directly on the chip, and therefore requires only a minimum of external components. ZigBee Stack in C language is provided by the microcontroller manufacturer. Method described below, was built on Z-stack version 2.5.1. Stack is not completely editable, large part is prebuilt in libraries. The following method uses for data access at physical layer function "macMemReadRxFifo".

2.2 Hamming Code

Following forward error correction method consists of two main parts, interleaver and Hamming encoder (7,4). Encoder and interleaver are included in the system to protect the transmitted data against bit errors. Hamming code falls into the category of self-correction codes, and it also belongs to the group of perfect codes, that means with the lowest possible redundancy. The algorithm generating and decoding parity bits, is easily implementable into 8-bit microcontroller. Encoding cycle costs are important especially in low power ZigBee wireless, because every incoming packet must be tested by FEC at receiving side. From this perspective Hamming code is most suitable candidate. The principle of a Hamming code (7,4) is assigned from three parity bits (see equation (1) (2) (3)) for every four bits protected. Parity bits are located at positions of second power – 1,2,4), [5]. Calculation of parity bits can be written:

$$p_1=b_1 \oplus b_2 \oplus b_4 \quad (1)$$
$$p_2=b_1 \oplus b_3 \oplus b_4 \quad (2)$$
$$p_3=b_2 \oplus b_3 \oplus b_4 \quad (3)$$

Where p_1, p_2, p_3 are parity bits, resulting from XOR addition of input bits b_1 to b_4. Result is written in format:

$$p_1\ p_2\ b_1\ p_3\ b_2\ b_3\ b_4$$

This 7-bit word allows recognize and correct one single error. The detecting calculation is based in following three equations:

$$s_1=b_1 \oplus b_2 \oplus b_4 \oplus p_1 \quad (4)$$
$$s_2=b_1 \oplus b_3 \oplus b_4 \oplus p_2 \quad (5)$$
$$s_3=b_2 \oplus b_3 \oplus b_4 \oplus p_3 \quad (6)$$

Where the vector consisting of bits (s1, s2, s3) represents an Error syndrome. When the Error syndrome is zero, the code word contains no errors, or more than one error. If there is one error in transmission, error syndrome corresponds to position of fault bit, in [4]. It implies that when more than one error is given, the calculation may be correct, but the resulting syndrome does not correspond to reality. For this case can be used extended Hamming code (8,4). This algorithm assigns one more parity bit to check the whole word. Then you can still fix one error, but also another one error detect. Because following FEC method contains CRC, there is no reason to use this parity bit.

2.3 Block Interleaver

PHY layer of ZigBee uses spread spectrum method - replacing each four data bits by 32 chips. If a sufficient amount of bit errors occurs in transmission, backward process will not be able to replace chips with correct data bits and cluster error will occur. More than two separate errors in distance $n \leq 7$ affects wrong function of Hamming code. To prevent this case the Block data Interleaver is included in the processing.

Block interleaver is used to increase the distance between incorrect bits. Interleaving goal is to change the distribution of errors in the data block, spread clusters of errors to discrete errors. Discrete errors in distance n>7 can be corrected by Hamming code, [4]. Interleaver is built from virtual table, where data are written in columns and output data is read by rows. Figure 2 shows the principle for interleaving 4x4. The numbers in cells indicates the sequence position of input bits.

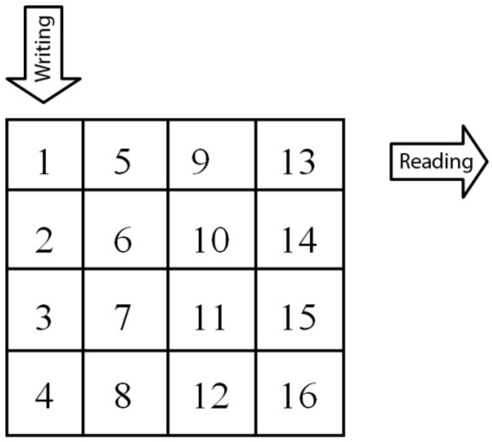

Fig. 2: Block interleaver matrix

The design of interleaver is determined by ZigBee standard itself, and also from the measurement and simulation. Measurements shows that amount of the cluster highly depend on interfering element type, distance, and the signal strength. So chosen parameters of interleaver are not determined by measurement of cluster error rate only, but also with regard to the highest possible efficiency in the capabilities of ZigBee data packet and the acceptable load of the microcontroller. Size of the interleaver matrix was with respect to the maximum interleaving depth and a relatively large space in the data packets defined to 28 * 27. Matrix generates 756 bits, which corresponds to 108 code words of Hamming code. Final data capacity of one coded packet is 432 bits.

2.4 Efficiency of Forward error correction above PHY Layer

Because this method is located above the physical layer, their impact doesn't cover all the transmission. To identify, which data can be covered by FEC (Fig. 3) and which can't, follows a transmission structure summary (Fig. 4)

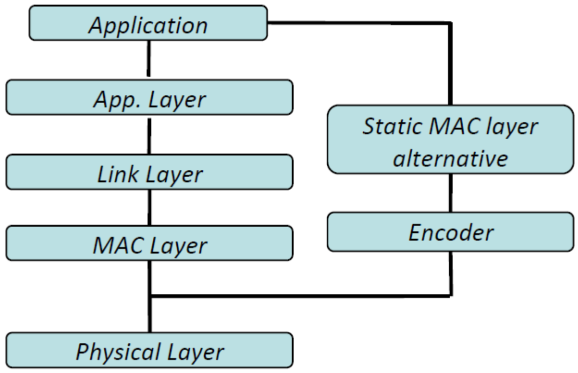

Figure 3: Scheme of FEC data connection

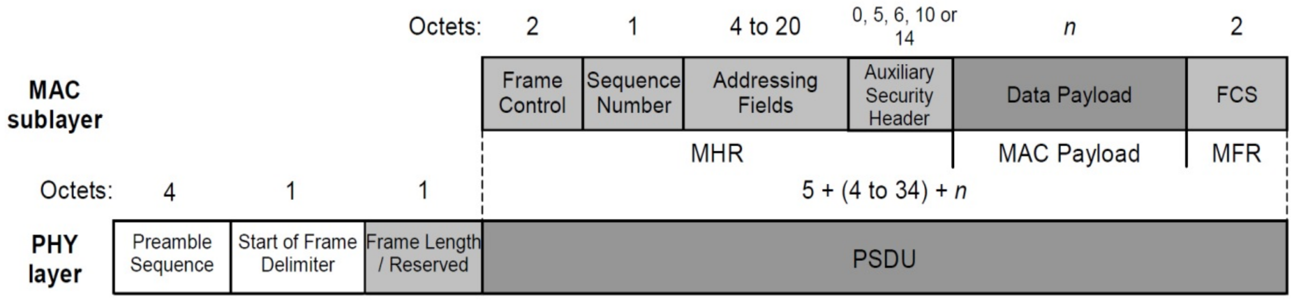

Figure 4: Frame format of 802.15.4 , in [3].

Frame begins by the Preamble, SoF delimiter and Frame length value, total of 48 bits which cannot be covered by provided forward error correction method, because it's given by Physical layer and cannot be changed without incompatibility issue. If the compatibility with other ZigBee nodes is important, MAC sublayer should be untouched too. Anyway, algorithm of this method shall decode all incoming packets, because alternative MAC header is included under FEC coding. That implies, that the MAC header is not important from perspective of probability of transmission at end point. Coded frames will be compatible with all other ZigBee nodes, they will be able to route this frames as any other. From this perspective only PHY header can't be covered by FEC and shall be error free in transmission. FEC method protection is 94% of PHY frame. If error occurs in covered part, MAC header or FCS, can be corrected, if error will occur in PHY header, frame will be lost.

2.5 Experimental measurement

Aim of experiment was to verify efficiency of described method in increasing reliability of transmission. As experimental hardware was used Development boards Texas Instruments SmartRF05, where SoC microcontrollers CC2530F256 are used. These modules have output power 4.5 dBm and receiving sensitivity -97 dBm. Experimental network consist from Coordinator and Router nodes, where Coordinator was a transmitter and Router receiver. Software in modules was upgraded with described FEC method and measurement application. When network establishment was done, application in Coordinator starts sending predefined amount of coded frames to Router. A coded frame contains random data, generated for each frame separately and alternative 16 bit checksum in coded area. Router is decoding all incoming frames with correct frame length, and checks CRC value. If CRC value is correct, router increments amount of "coded way" received packet. Simultaneously, application counts all incoming data frames received by sublayers of Z-Stack. Flow chart of receiver application is described by Fig. 5. ZigBee network was established at channel 11.

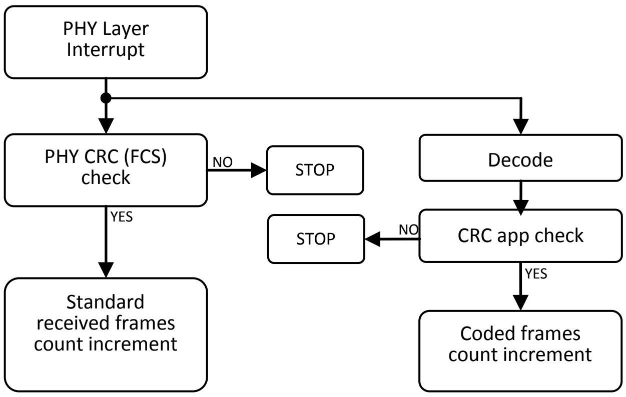

Fig. 5: Receiver application algorithm

As coexistence partner was chosen WiFi 802.11g link. This network was built from two main parts, WiFi Router US Robotics USR8054, and Tablet Samsung P3110. Packets were generated by PC connected into Router by UTP cable at speed 100 Mbit.s^{-1}, and sent to IP address of tablet over WiFi. Various packet sizes, was generated by Nping software, where following setting was used:

- 192.168.123.101
- --data-length *X*
- --delay 0
- -c 2^{32}
- --send-ip

X parameter is length of user data, which was changed for each measurement.

Wireless connection between Router and Tablet, was set to 1 channel and connection speed 54 Mbit.s^{-1}. That implies, the Physical layer used 64-QAM modulation and data was coded with convolutional code in ¾ ratio. Data stream was sent through 48 subchannels, where each symbol means 6 bits. Symbol duration is 4 µs. Over ZigBee network, only one type of packet was transferred, namely 108 Bytes of total length (13 B of ZigBee sublayers and 95 B of Data). That implies, since the symbol duration is 16 µs and DSSS coding (4/32) is used, 27.6 ms for each frame.

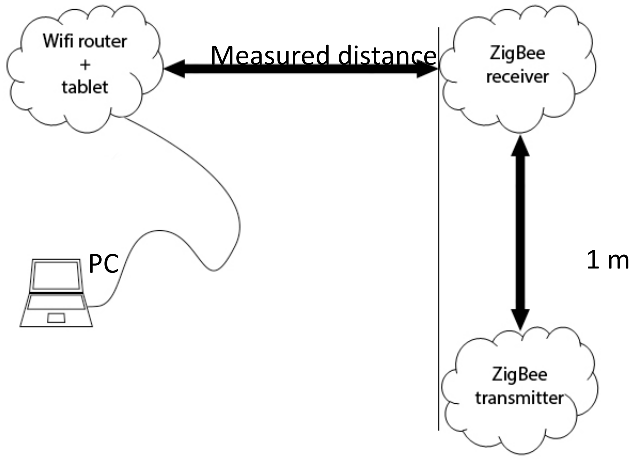

Fig. 6: Measurement equipment positioning

ZigBee nodes were mounted on tripod 1.5 m above ground, in 1 m distance. WiFi transceivers were in immediate distance, mounted on tripod in 1.5 m height. Distance between WiFi pair and ZigBee pair was gradually increased for each measurement. Distance was measured between ZigBee receiver and WiFi pair (Fig. 6). For each distance was sent defined amount of packets over ZigBee network, and registered values of correctly delivered packets on receiver. For each distance has been done five measurements and then was calculated PER value according to the equations (7) and (8). Measurement was repeated for various packet length transmitted over WiFi.

$$PER_{ZigBee} = 1 - \frac{\text{amount of received frames with correct } \mathrm{CRC}_{phy}}{\text{total of sent frames}} \qquad (7)$$

$$PER_{fec} = 1 - \frac{\text{amount of received frames with correct } \mathrm{CRC}_{app}}{\text{total of sent frames}} \qquad (8)$$

2.6 Experiment Area

Measurement was done in open area, where wasn't in 3 km radius no residential area or high-voltage lines. Before experiment was measured radio background level around 11 ZigBee channel, result is shown on Fig. 7. Measurement was done with WiSpy spectrum analyzer and Chanalyzer Software. As can be seen on Fig. 7, noise level was under -105 dBm.

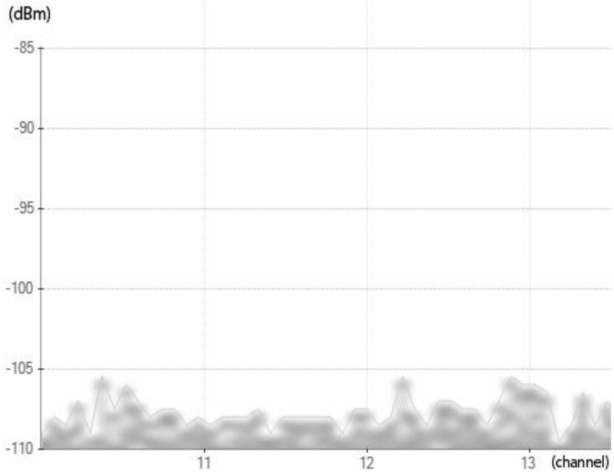

Fig. 7: Radio background at experiment area

3 Results and Discussion

Figure 8 shows results of coexistence measurement with length of WiFi packet 76B (31.2 µs). Mean time between WiFi packets was 3 ms. From this parameters can be deducted, that in each ZigBee packet (27.6 ms) 9 collisions with WiFi packet can occur. Each collision may take up to 31.3 µs. That implies, interference can persist for 3 consecutive ZigBee symbols (16 µs each). Three symbol errors can result into 12 mistaken chips in row, and it means cluster of errors in length of 8 bits.

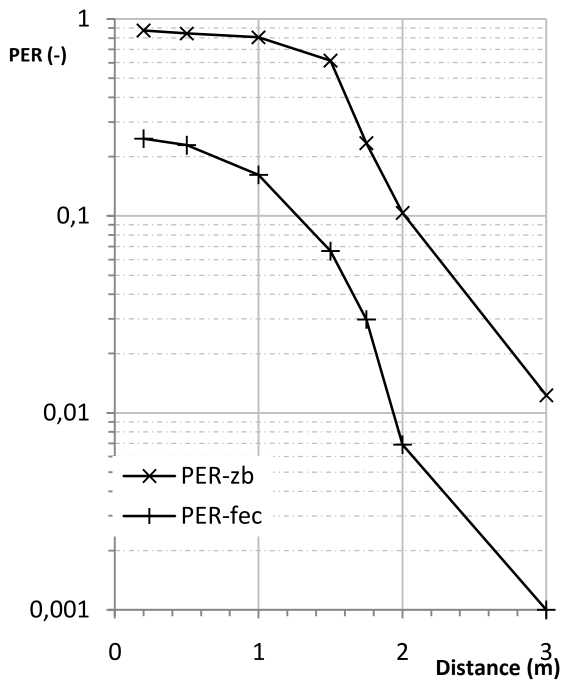

Fig. 8: FEC effect when operating under WiFi 802.11g coexistence and packet size 76 B

Figure 9 shows effect of FEC under 802.11g coexistence with packet size 188 B (47.9 µs). Mean time between WiFi packets was 1 ms. Under this circumstances can occur an error in three consecutive ZigBee symbols like in previous case, maximum is 8 burst errors in a row. Due to packet spacing, can occurs 26 clusters in each ZigBee frame.

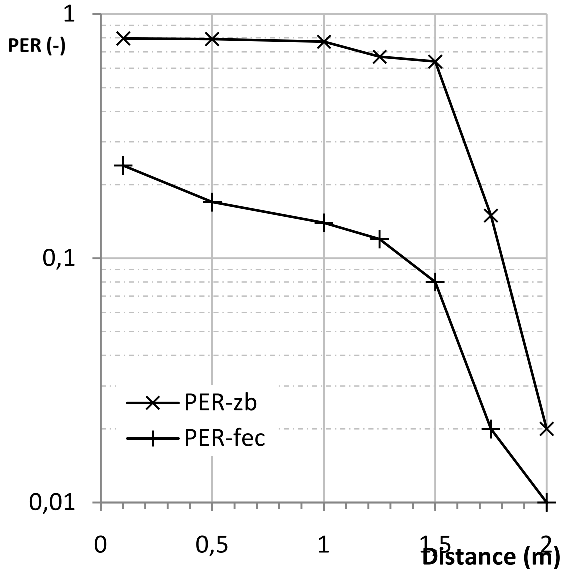

Figure 9: FEC effect when operating under WiFi 802.11g coexistence and packet size 188 B

Figure 10 shows FEC impact when WiFi packet is set to 316 B (66.8 µs), and meant time between packets is 1 ms. Compared to the previous case, now can be occurred 5 consequent ZigBee symbols, which is resulting into 20 wrong chips and, as before, two error clusters in a row. As before, interference can occur 26 times for each ZigBee frame.

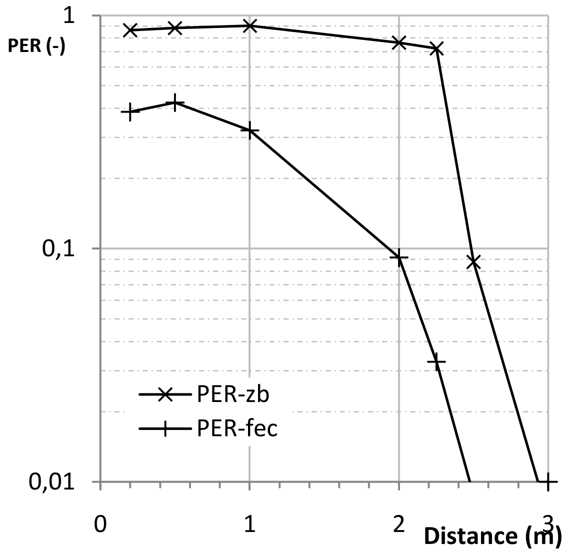

Figure 10: FEC effect when operating under WiFi 802.11g coexistence and packet size 316 B

Next case (Fig. 11) shows FEC impact when WiFi packet length is set to 572 B (104.7 µs). At this time can be occurred 8 ZigBee symbols in a row, which means 32 chips, and again two clusters of errors with length 8 bits. As before, interference can occur 26 times for each ZigBee frame.

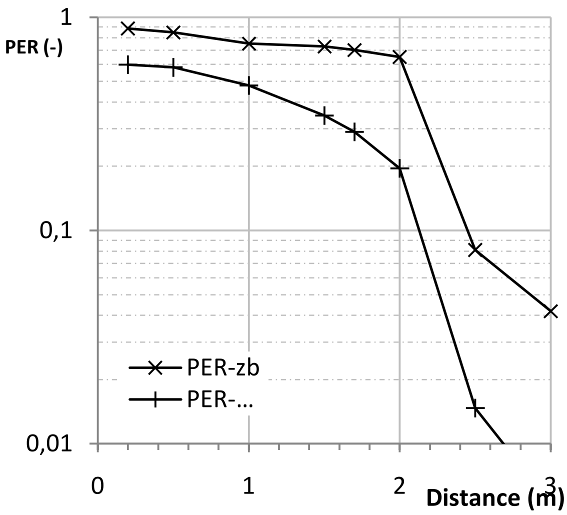

Figure 11: FEC effect when operating under WiFi 802.11g coexistence and packet size 572 B

Figure 12 shows results with length of WiFi packet 1532 B (247 µs) and mean time between packets 450 µs. Effect of FEC method under this coexistence variant is very low. Error can occur in 17 ZigBee symbols in a row, which means 68 chips and cluster of 12 bits. For each ZigBee frame can occur 40 collisions, 12 bits each maximum.

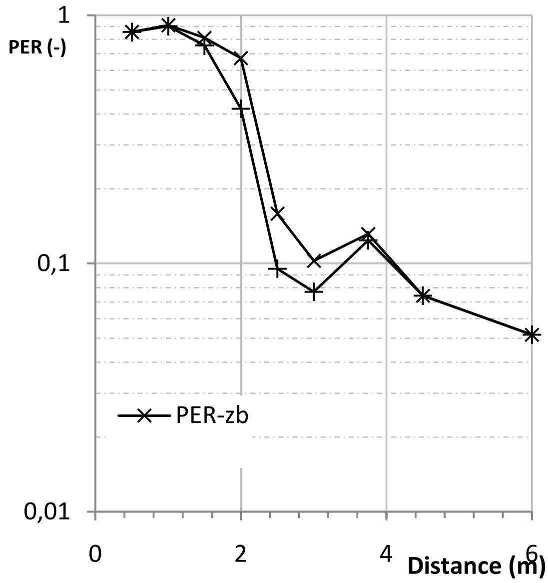

Fig. 12: FEC effect when operating under WiFi 802.11g coexistence and packet size 1532 B

As can be seen at Figure 13, significant benefit of described FEC method, is when coexisting WiFi is lowly loaded, mainly with packets below 512 B of length. With interfering packets 316 B of length or lower, difference between standard ZigBee transfer and FEC covered method is at same conditions about **Δ**PER 0.6, that means the "FEC packet" error probability is 60% lower.

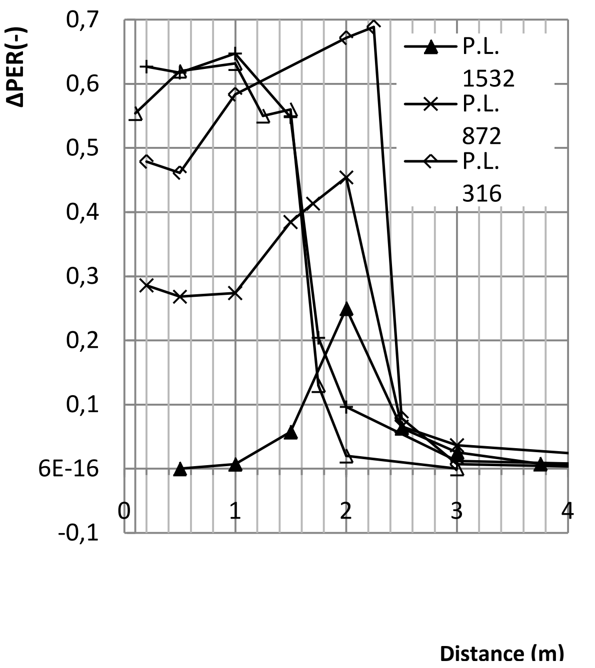

Fig. 13: Difference between standard ZigBee and FEC covered transmission

4 Conclusion

Hamming code (7,4) has information rate 0.57, that results into decreasing of packet capacity from 95 B to 54 B. However, this amount shall be decreased for 2 Bytes of CRC and the same alternative address of destination 1 or 2 Bytes, so the final frame capacity will be lowed of 7 Bytes (4 Bytes coded By Hamming code). That implies, that described Forward Error correction method decreases frame capacity of 50.5%. Experimental measurement in open area demonstrates benefits of this method under WiFi 802.11g coexistence. When WiFi is loaded with shorter packet lengths, FEC method can increase probability of successful transmission of 50-70% at same position.

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