# Bluetooth and IEEE 802.11b/g Coexistence Simulation

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**Abstract.** *This paper deals with the coexistence simulation of Bluetooth and Wi-Fi physical layers. Bluetooth and Wi-Fi systems share the same ISM 2.4 GHz frequency band and therefore using both systems in the same area may cause interference. A model of Bluetooth and IEEE 802.11b/g physical layers was made in Mathworks Matlab Simulink environment. A new simulation of Bluetooth and Wi-Fi coexistence is presented. The results in graphical form are introduced as a dependence of BER on $E_b/N_0$ and BER on power ratio of Bluetooth and Wi-Fi systems.*

## Keywords

Bluetooth, Wi-Fi, IEEE 802.11b, IEEE 802.11g, Coexistence.

## 1. Introduction

Bluetooth is an industrial specification for WPAN (Wireless Personal Area Network) networks, which operate in short-range radio frequency band. Bluetooth enables exchanging information between various devices, printing on Bluetooth printer and connecting various PC peripherals (wireless mouse, keyboard, hands-free, etc.).

The Bluetooth system is widely used in office environment, where it can be greatly disturbed by other sources of ISM 2.4 GHz interference. Strong interference can be caused by the Wi-Fi [1] communication standard, which uses the same ISM 2.4 GHz frequency band. Many portable devices support both communication standards and can be connected to the Wi-Fi access point and Bluetooth headset or Bluetooth modem at the same time. Bluetooth and Wi-Fi interference can be reduced by Adaptive Frequency Hopping (AFH) [2], but this noncollaborative method is implemented in Bluetooth 1.2 and later revisions of the standard. The present work deals with non-AFH coexistence simulations.

## 2. IEEE 802.11b Physical Layer

Wi-Fi is developed by IEEE 802.11 Task Group and is aimed on WLAN (Wireless Local Area Network) networks. Wi-Fi is mainly used for enabling mobile Internet connectivity in various devices (mobile phones, notebooks, etc.). IEEE 802.11 uses ISM (Industrial Scientific and Medical) 2.4 GHz frequency band and there are 13 overlapping 22 MHz wide frequency channels defined (Fig. 1). The most widespread specifications are IEEE 802.11b and IEEE 802.11g (Tab. 1).

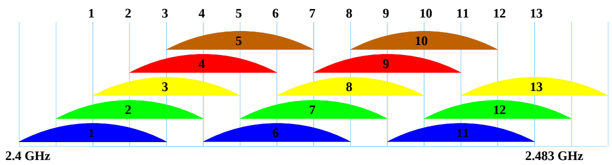


**Fig. 1.** Wi-Fi channels.

The first IEEE 802.11 physical layer specification released in 1997 is called DSSS (Direct Sequence Spread Spectrum) and employs Barker coding to achieve 1 Mbit/s (DBPSK) and 2 Mbit/s (DQPSK). In 1999, the IEEE 802.11b specification was released. It was enhanced with HR/DSSS (High Rate DSSS), which employs Complementary Code Keying and achieve data rates of 5.5 Mbit/s and 11 Mbit/s (Tab. 1).

| Standard version | Release | Data rates [Mbit/s] | Modulation | Coding |
|---|---|---|---|---|
| 802.11 | 1997 | 1, 2 | DBPSK and DQPSK | Barker c. |
| 802.11b | 1999 | 1, 2, 5.5, 11 | DBPSK a DQPSK | Barker c., CCK |
| 802.11g | 2003 | up to 54 | DBPSK to 64QAM | OFDM |
| 802.11a | 1999 | up to 54 | BPSK to 64QAM | OFDM |
| 802.11n | 2007-8 | up to 540 | DBPSK to 64QAM | OFDM, MIMO |

**Tab. 1.** IEEE 802.11 standards overview.

Standard IEEE 802.11b employs Barker Coding and CCK (Complementary Code Keying). IEEE 802.11b data rates are summarized in Tab. 2.

| Data rate | Code length | Modulation | Sym. rate [MSps] | bits/ symbol | System |
|---|---|---|---|---|---|
| 1 Mbit/s | 11 (Barker c.) | DBPSK | 1 | 1 | DSSS |
| 2 Mbit/s | 11 (Barker c.) | DQPSK | 1 | 2 | DSSS |
| 5.5 Mbit/s | 4 (CCK) | DQPSK | 1.375 | 4 | HR/DSSS |
| 11 Mbit/s | 8 (CCK) | DQPSK | 1.375 | 8 | HR/DSSS |

**Tab. 2.** IEEE 802.11b - data rates specifications.

## 2.1 Barker Coding and Complementary Code Keying

Barker coding is a modulation technique, that was used in the first specification of IEEE 802.11 (1997) and it provides 1 Mbps (2 Mbps) data rates while using BPSK (QPSK). It works by taking a data stream of zeros and ones and modulating it with a second pattern, 11 chips long sequence (Barker code) 10110111000.

$$C_{0,..,7} = \left\{ \begin{array}{l} e^{(j\varphi_1 + j\varphi_2 + j\varphi_3 + j\varphi_4)}, e^{(j\varphi_1 + j\varphi_3 + j\varphi_4)}, \\ e^{(j\varphi_1 + j\varphi_2 + j\varphi_4)}, -e^{(j\varphi_1 + j\varphi_4)}, \\ e^{(j\varphi_1 + j\varphi_2 + j\varphi_3)}, e^{(j\varphi_1 + j\varphi_3)}, \\ -e^{(j\varphi_1 + j\varphi_2)}, e^{(j\varphi_1)} \end{array} \right\} \quad (1)$$

The 802.11b ”High Rate” amendment to the standard (ratified 1999) added two higher speeds (5.5 and 11 Mbps) to IEEE 802.11 specification. Rather than the two 11-bit Barker codes, Complementary Code Keying uses a set of 64 eight chips long unique complex code words, thus up to 6 bits can be represented by any code word (instead of the 1 bit represented by a Barker symbol). Data stream is devided into 4 dibits, which are represented by 4 phases $\varphi_1$, $\varphi_2$, $\varphi_3$ and $\varphi_4$ [1]. Complementary codes are evaluated with help of (1). Every 4 bits or 8 bits are modulated to 8 chips $C_0$ to $C_7$ according to the data rate of 5.5 or 11 Mbit/s.

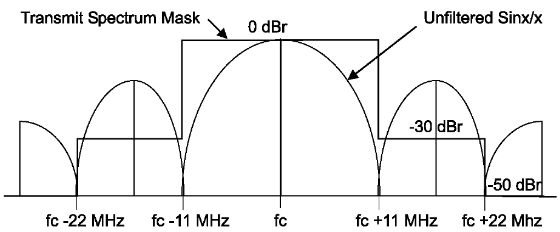


**Fig. 2.** DSSS transmit spectrum mask [1].

Wi-Fi DSSS physical layer uses pulse shaping to meet the frequency spectrum mask specified in the standard (Fig. 2). Square Root Raised Cosine filter with roll-off factor 0.35 is implemented in the transmitter and in the receiver. Implementation of Compelementary Code Keying is furthermore explained in article [6].

# 3. IEEE 802.11g Physical Layer

The IEEE 802.11 standard was upgraded in 2003 with the new IEEE 802.11g specification, which employs OFDM modulation and data rates up to 54 Mbit/s in the same frequency band. The IEEE 802.11g standard is backward compatible with the older IEEE 802.11b. Higher data rates use 16QAM and 64QAM modulations according to Tab. 3.

| Data rate | Modulation | Coding rate ($R$) | Coded bits per carrier ($N_{\mathrm{BPSC}}$) | Coded bits per OFDM symbol ($N_{\mathrm{CBPS}}$) | Data bits per OFDM symbol ($N_{\mathrm{DBPS}}$) |
|---|---|---|---|---|---|
| 6 Mbit/s | BPSK | 1/2 | 1 | 48 | 24 |
| 9 Mbit/s | BPSK | 3/4 | 1 | 48 | 36 |
| 12 Mbit/s | QPSK | 1/2 | 2 | 96 | 48 |
| 18 Mbit/s | QPSK | 3/4 | 2 | 96 | 72 |
| 24 Mbit/s | 16QAM | 1/2 | 4 | 192 | 96 |
| 36 Mbit/s | 16QAM | 3/4 | 4 | 192 | 144 |
| 48 Mbit/s | 64QAM | 2/3 | 6 | 288 | 192 |
| 54 Mbit/s | 64QAM | 3/4 | 6 | 288 | 216 |

**Tab. 3.** IEEE 802.11g - data rates specification.

## 3.1 Normalization

The subcarriers are modulated with BPSK, QPSK, 16QAM or 64QAM, depending on the data rate requested. A gray coded constellation mappings of QPSK, 16QAM and 64QAM modulations are normalized with the factor $K_{\mathrm{MOD}}$ to the same average energy and power (Tab. 4).

| Modulation | $K_{\mathrm{MOD}}$ |
|---|---|
| BPSK | 1 |
| QPSK | $1/\sqrt{2}$ |
| 16QAM | $1/\sqrt{10}$ |
| 64QAM | $1/\sqrt{42}$ |

**Tab. 4.** Modulation dependent normalization factor.

## 3.2 Convolutional Coding

Bits are coded by a convolutional encoder with coding rate $R$ = 1/2, 2/3 or 3/4, corresponding to the desired data rate (Fig. 3). The convolutional encoder uses the generator polynomials, $g_0 = 133_8$ and $g_1 = 171_8$, of rate $R$ = *1/2*.

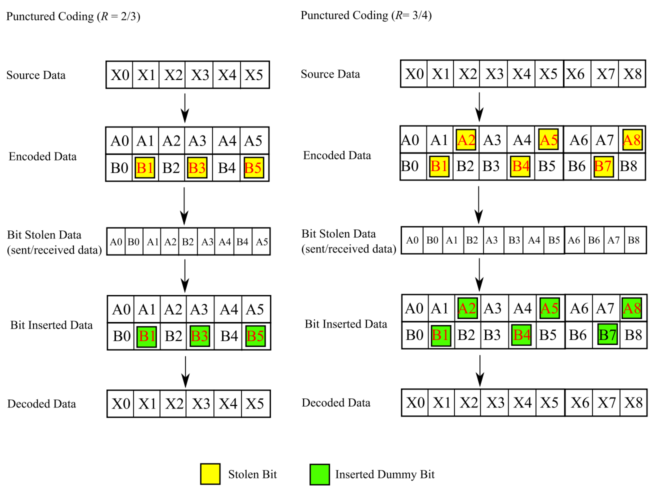


**Fig. 3.** Convolutional coding, $R$ = 2/3, 3/4 - puncturing.

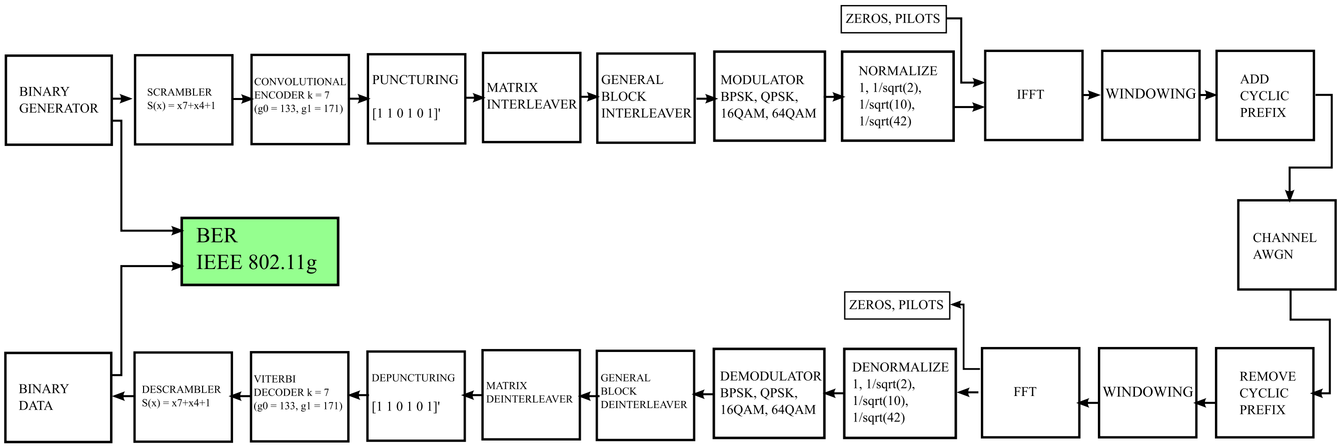


**Fig. 4.** Block diagram of the IEEE 802.11g Matlab Simulink model.

Higher rates are derived from it by employing "puncturing". Received bits are decoded with help of the Viterbi decoder. Modulation and coding parameters of the IEEE 802.11g standard can be seen in Tab. 3. An example of bit stealing and bit inserting procedure is depicted in Fig. 3.

### 3.3 Data Interleaving

All encoded data bits are interleaved by a block interleaver with a block size corresponding to the number of bits in a single OFDM symbol, $N_{\mathrm{CBPS}}$. The interleaver is defined by a two-step permutation. The first permutation ensures that adjacent coded bits are mapped onto nonadjacent subcarriers. The second permutation ensures that adjacent coded bits are mapped alternately onto less and more significant bits of the constellation and, thereby, long runs of low reliability (LSB) bits are avoided.

The index of the coded bit before the first permutation shall be denoted by *k*; *i* shall be the index after the first and before the second permutation; and *j* shall be the index after the second permutation, just prior to modulation mapping.

The first permutation is defined by the rule

$$\begin{aligned} &i = (N_{\mathrm{CBPS}}/16)(k \bmod 16) + \mathrm{floor}(k/16), \\ &k = 0, 1, ...., N_{\mathrm{CBPS}} - 1. \end{aligned} \tag{2}$$

The function floor (.) denotes the largest integer not exceeding the parameter. The second permutation is defined by the rule

$$\begin{aligned} &j = s \cdot \mathrm{floor}(i/s) + (i + N_{\mathrm{CBPS}} - \mathrm{floor}(16 \\ &\qquad \cdot i/N_{\mathrm{CBPS}})) \bmod s) \\ &i = 0, 1, ...., N_{\mathrm{CBPS}} - 1. \end{aligned} \tag{3}$$

The value of *s* is determined by the number of coded bits per subcarrier, $N_{\mathrm{BPSC}}$, according to

$$s = \max(N_{\mathrm{BPSC}}/2, 1). \tag{4}$$

The deinterleaver, which performs the inverse relation, is also defined by two permutations [1]. The block scheme of the IEEE 802.11g Matlab Simulink simulation can be seen in Fig. 4.

## 4. Bluetooth Physical Layer

The Bluetooth system operates in the 2400.0 - 2483.5 MHz license free ISM (Industrial, Scientific and Medical) frequency band. RF channels are spaced 1 MHz and are arranged by channel number *k* according to the following formula

$$f = 2402 + k \ \text{ MHz}, \quad k = 0, ...., 78. \tag{5}$$

Two data transmission modes are defined. A mandatory mode, called *Basic Rate*, uses a shaped, binary FM modulation to minimize transceiver complexity. An optional mode, called *Enhanced Data Rate*, uses PSK modulation and has two variants: $\pi/4$-DQPSK and 8DPSK. The symbol rate for all modulation schemes is 1 Ms/s [3].

### 4.1 Basic Rate (BR)

Basic Rate mode is a mandatory part of the Bluetooth specification. The modulation is GFSK (Gaussian Frequency Shift Keying) with bandwidth-bit period product BT=0.5. Modulation index is 0.32. You can see the Bluetooth BR packet format in Fig. 5.

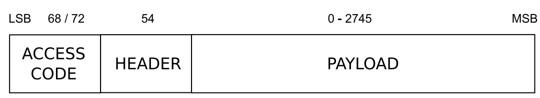


**Fig. 5.** Bluetooth BR packet format.

## 4.2 Enhanced Data Rate (EDR)

A key characteristic of the Enhanced Data Rate mode is that the modulation scheme is changed within the packet (Fig. 6). The access code and packet header (Fig. 7) are transmitted with the Basic Rate 1 Mbit/s GFSK modulation scheme, whereas the subsequent synchronization sequence, payload, and trailer sequence are transmitted using the Enhanced Data Rate PSK modulation scheme. Simulation of Bluetooth EDR physical layer is provided in article [5].

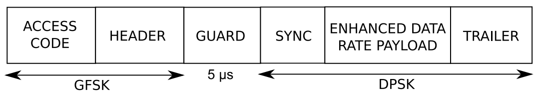


**Fig. 6.** Bluetooth EDR packet format.

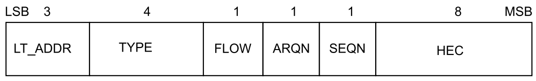


**Fig. 7.** The description of a bluetooth header.

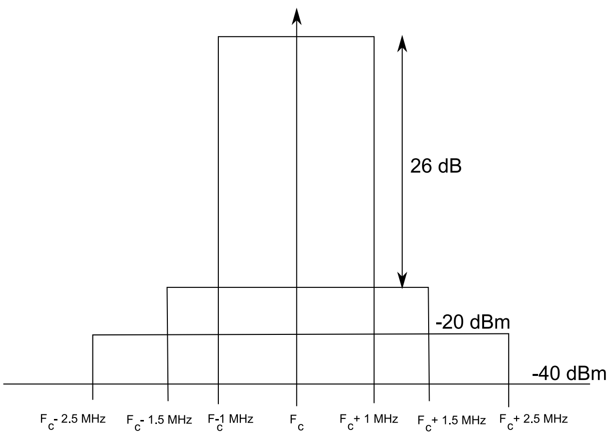


**Fig. 8.** Bluetooth spectral mask.

## 4.3 Data Whitening

Both the header and the payload are scrambled with a data whitening word in order to randomize the data and to minimize DC bias in the packet. Scrambling is performed prior to the FEC encoding.

The whitening word is generated with the following polynomial

$$G(z) = z^{-7} + z^{-3} + 1. \tag{6}$$

The whitening word is generated with the linear feedback shift register (LFSR). The LFSR register is initialized with the portion of the master Bluetooth clock, CLK6-1, extended with position 0, CLK2 written to position 1, etc.

There is no reinitialization of the shift register between packet header and payload. For enhanced data rate packets, whitening is not applied to the guard, synchronization and trailer portions of the EDR packets. During the period, where whitening is not applied, the LFSR is paused [3].

## 4.4 Error Correction

There are defined 3 ways of error detection and correction in Bluetooth specification.

**1/3 rate FEC**

A simple 3-times repetition FEC code is used for the header. The repetition is implemented by repeating each bit three times ($b_0b_0b_0b_1b_1b_1b_2b_2b_2b_3b_3b_3...etc.$). FEC 1/3 is applied on header in each type of the Bluetooth packet.

**2/3 rate FEC**

The second type of the FEC scheme is a (15,10) shortened Hamming code. LFSR register with S1 and S2 switches is depicted in Fig. 9. The generator polynomial is $(x + 1).(x^4 + x + 1)$. The 10 information bits are sequentially fed into the LFSR with the switches S1 and S2 set in position 1. Then, after the final input bit, the switches S1 and S2 are set in position 2, and the five parity bits are shifted out. Subsequently, each block of 10 information bits is encoded into a 15 bit codeword. This code can correct all single errors and detect all double errors in each codeword. If the length of the information bits is less than 10, it is followed by zeros till the register is full.

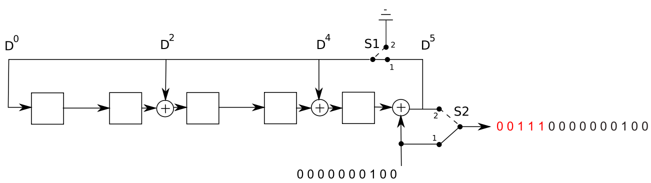


**Fig. 9.** Block diagram of the 2/3 FEC code implementation.

**ARQ scheme for the data**

With an automatic repeat request scheme packets are transmitted until acknowledgement of a successful reception is returned by the destination (or timeout exceeded). The acknowledgement information shall be included in the header of the return packet. The ARQ scheme is only used on packets that have a CRC. If a device successfully receives CRC, ARQN bit is set to 1. If there is a fault in HEC, CRC or Access Code is not detected, ARQN bit is set to 0. CRC-16 with generation polynomial $x^{16} + x^{12} + x^5 + 1$ is used.

FEC coding is used for lowering the need for packet retransmission. There are many types of packets with each type of FEC defined. When good conditions in the communication channel are present, the suitable type of the packet is used.

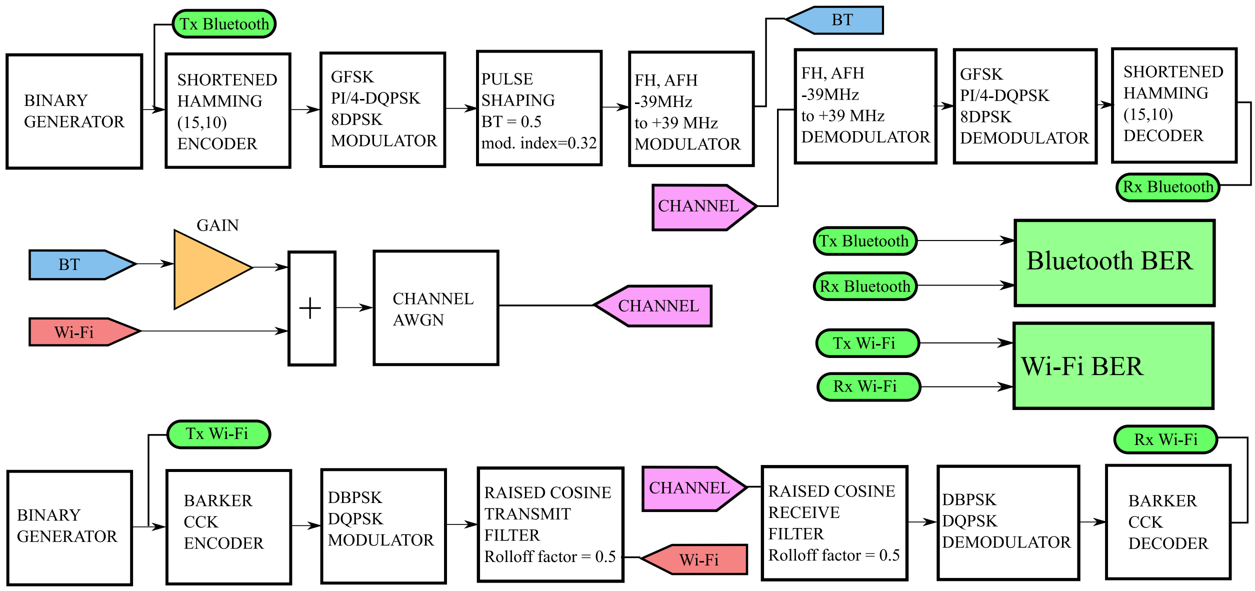


**Fig. 10.** Simplified block diagram of the IEEE 802.11b and Bluetooth coexistence simulation.

# 5. Simulation of Coexistence

Radio frequency simulations are very computationally intensive tasks, therefore all simulations have been made by equivalent baseband simulations with complex envelope [7]. Simulations of coexistence have been made in Matlab Simulink environment with Communication Blockset extension. Simplified block diagram of the IEEE 802.11b and Bluetooth 1Mbit/s simulation can be seen in Fig. 10. The IEEE 802.11g and Bluetooth coexistence simulation is analogical to Fig. 10, but the physical layer of IEEE 802.11g from Fig. 4 is used instead of IEEE 802.11b physical layer.

Baseband equivalent simulation in frequency band from -39 to 39 MHz provides faster simulation than radio frequency simulation in frequency band from -2.402 to 2.480 GHz. Bluetooth standard uses all 79 carriers frequencies with bandwidth of 1 MHz according to the following formula

$$f = -39 + k \ \text{MHz}, \quad k = 0, ...., 78 \tag{7}$$

where $k$ is number of the channel of the Bluetooth system. Wi-Fi (IEEE 802.11b/g) system is simulated in baseband and the center frequency is set to 0 MHz.

## 5.1 IEEE 802.11b and Bluetooth Simulation

Bluetooth and Wi-Fi signals are added together (Fig. 10). The power of IEEE 802.11b signal is normalized and set to 0 dBm. The power of the Bluetooth signal is normalized and adjusted by 1 dB step from -20 to 20 dBm. Both signals are sampled and filtred to the same sampling rate according to Fig. 11.

The mean power of the digital baseband signal can be counted with help of the following formula

$$P_d = \frac{1}{N}\sum_{n=1}^{N}(|x(n)|^2), \tag{8}$$

where $N$ is the number of samples in a measured signal and $x(n)$ is the amplitude of the sample. The power is counted for each frame.

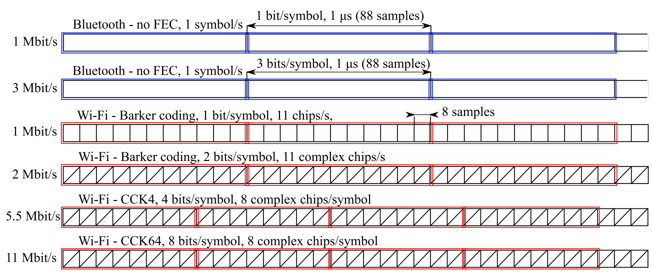


**Fig. 11.** IEEE 802.11b vs Bluetooth simulation - sampling realations.

You can see a power spectrum of the Bluetooth and IEEE 802.11b simulation compared to the real signals measurement by a spectral analyzer in Fig. 13. Power of Bluetooth is set to -10 dBm and power of IEEE 802.11b is set to 0 dBm in the simulation and in the measurement, too. As you see, the power spectrum of simulated signals is equal to the power spectrum that is displayed by the spectral analyzer.

You can see results of IEEE 802.11b transmission in presence of Bluetooth interference in Fig. 12. There is Bluetooth 1 Mbit/s interference and Bluetooth 3 Mbit/s interference compared. As you can see, the 3 Mbit/s Bluetooth data rate causes a slightly higher inteferences and that's why IEEE 802.11b has better performance with Bluetooth 1 Mbit/s interferer. That can be caused because of the narrower Bluetooth 1 Mbit/s (GFSK) bandwidth when compared to the Bluetooth 3 Mbit/s (8DPSK) bandwidth.

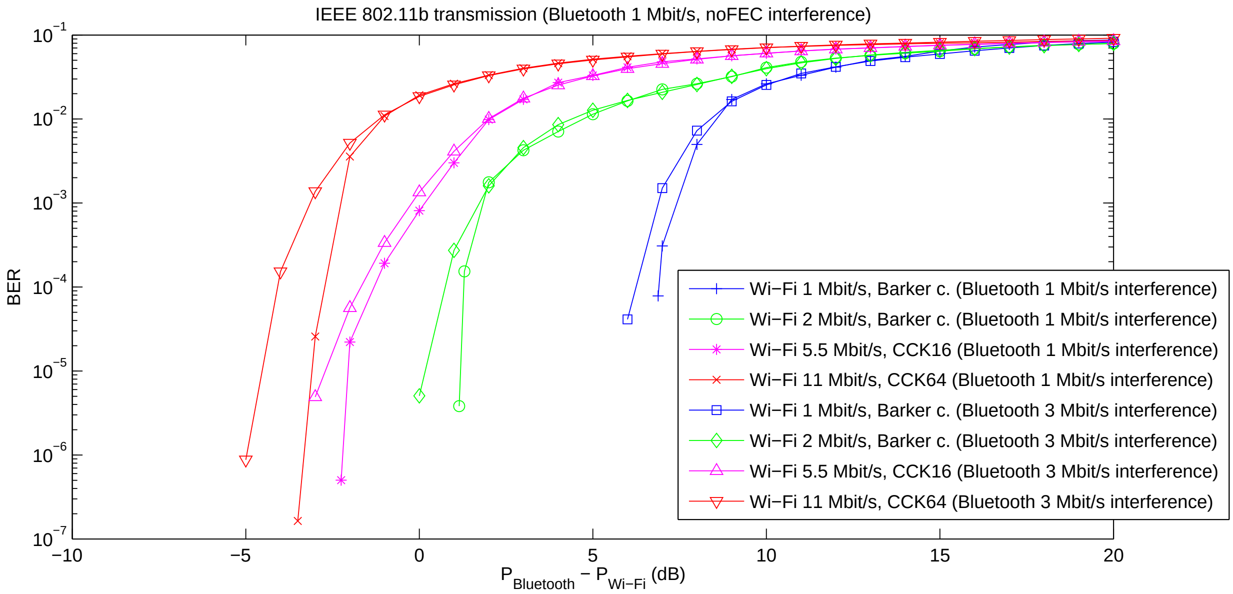


**Fig. 12.** IEEE 802.11b data transmission in presence of Bluetooth (1 Mbit/s) interference.

It is also obvious that BER of IEEE 802.11b system is in the worst case 10 % which equals to interference in 20 % of the band (16 MHz). This means that the IEEE 802.11b system is distored only for frequencies that collide with the Wi-Fi 16 MHz wide frequency band.

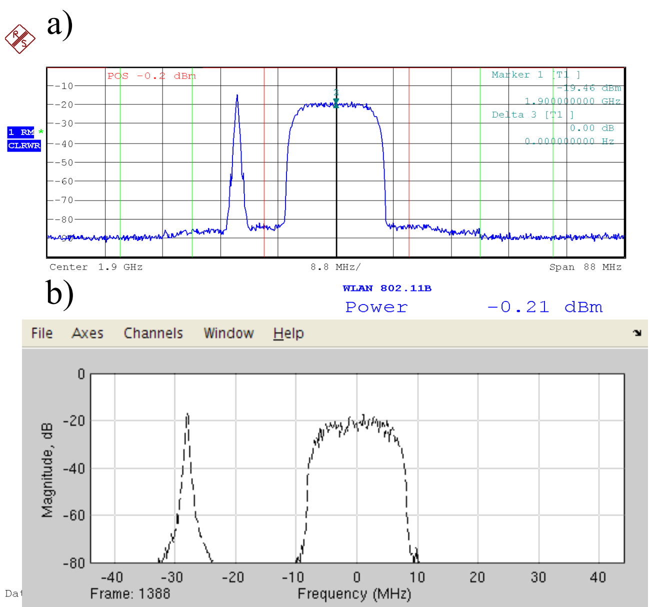


**Fig. 13.** Power spectrum of Bluetooth 1 Mbit/s and IEEE 802.11b 11 Mbit/s systems coexistence: $P_{\mathrm{Bluetooth}}$ = -10 dBm; $P_{\mathrm{Wi-Fi}}$ = 0 dBm
a - Real signals measurement
b - Matlab simulation.

Coexistence simulation was run in cycles, where Bluetooth signal hops over all 79 channels through one cycle and therefore probability of visiting particular Bluetooth channel in the whole simulation was exactly 1/79. Results of Bluetooth data transmission and IEEE 802.11b 11 Mbit/s interference are presented in Fig. 14. The best result has the 2 Mbit/s data rate, which corresponds with the theory, where $\pi$/4-DQPSK (2 Mbit/s) has better performance than 2FSK (1 Mbit/s) and 8DPSK (3 Mbit/s) modulation technique [8], [9]. Simulation also shows, that Bluetooth 2,3 Mbit/s has the smallest maximum BER value. This can be caused by better immunity of DPSK modulation. Bluetooth 2 and 3 Mbit/s data rate uses Raised Cosine filtering with factor 0.4 intead of Gaussian filtering that is used in Bluetooth 1 Mbit/s data rate.

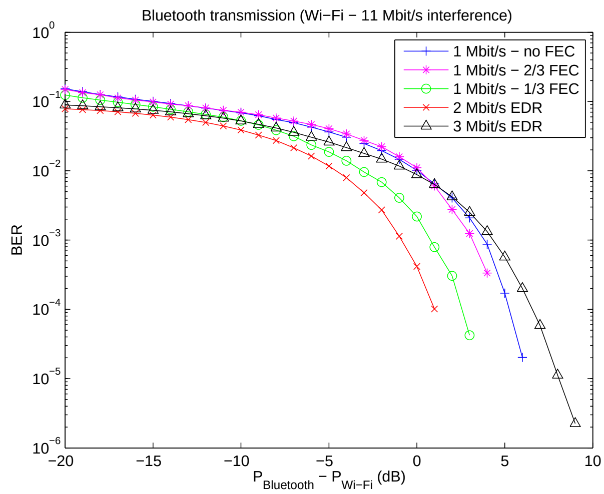


**Fig. 14.** Bluetooth transmission in presence of IEEE 802.11b (11 Mbit/s) interference.

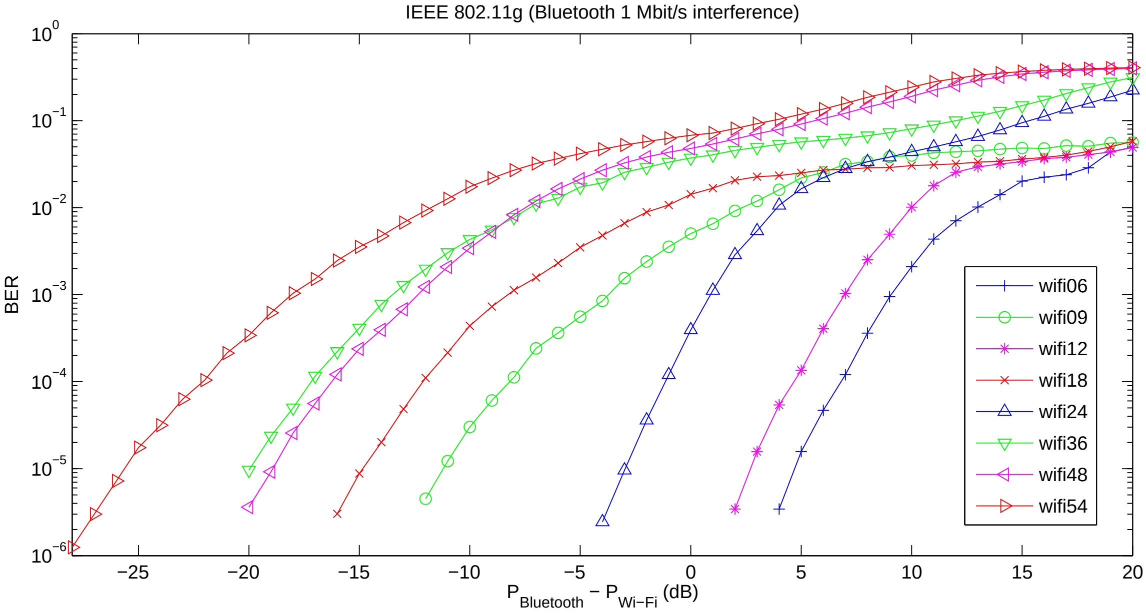


**Fig. 15.** Transmission of IEEE 802.11g - Bluetooth 1 Mbit/s interference.

## 5.2 IEEE 802.11g and Bluetooth Simulation

IEEE 802.11g and Bluetooth signals must have the same number of samples per time and both systems simulation must satisfy the Shannon theorem for simulation in -39 to 39 MHz frequency band. The sampling frequency was selected 128 samples per 1 µs. The length of the OFDM symbol is 4 µs and therefore 512 point IFFT is used. IEEE 802.11g signal is padded with zeros in frequency domain. IEEE 802.11g signal is normalized to the power of 0 dBm (Fig. 4) after the normalization and IFFT block processing.

Using of punctured convolutional codes in the IEEE 802.11g specification has its relevance, when AWGN channel is used (Fig. 18). Coexistence simulation shows that it is better to use non-punctured codes even a modulation technique with more states. For example: data rate of 24 Mbit/s has better performance than 18 Mbit/s, because of the punctured codes degradation (Fig. 15).

The lowest IEEE 802.11g bit error rates are achieved for mandatory data rates that are using non-punctured codes (6 Mbit/s, 12 Mbit/s and 24 Mbit/s - Fig. 15).

From Fig. 12, 14 and 15 it is clear that IEEE 802.11g and Bluetooth signals cannot have less than $10^{-5}$ BER at the same time. On the other hand, when $P_{\mathrm{Bluetooth}} - P_{\mathrm{IEEE802.11b}}$ is approximately 5 dB, Bluetooth 1 Mbit/s and 2 Mbit/s can successfully coexist with IEEE 802.11b and $BER < 10^{-5}$.

It is also clear that signals are degraded merely in the shared 16 MHz wide frequency band. This is illustrated by the Fig. 16 and 17. You can see a power spectrum of IEEE 802.11g and Bluetooth in Fig. 16 when no collision is present and Fig. 17 when both systems share the same frequency band. Increased interference can be seen in constellation diagrams.

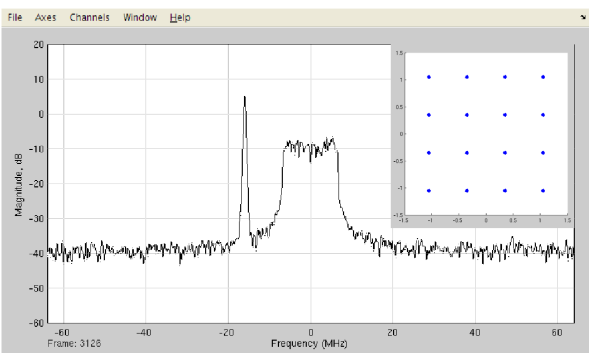


**Fig. 16.** IEEE 802.11g with Bluetooth (1 Mbit/s) interference - no collision, $P_{\mathrm{Bluetooth}} - P_{\mathrm{Wi-Fi}} = 0$ dB.

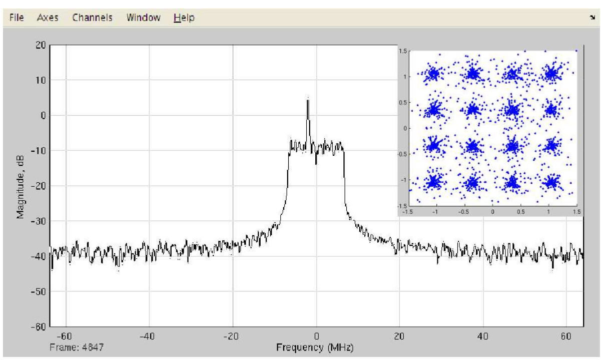


**Fig. 17.** IEEE 802.11g with Bluetooth (1 Mbit/s) interference - collision, $P_{\mathrm{Bluetooth}} - P_{\mathrm{Wi-Fi}} = 0$ dB.

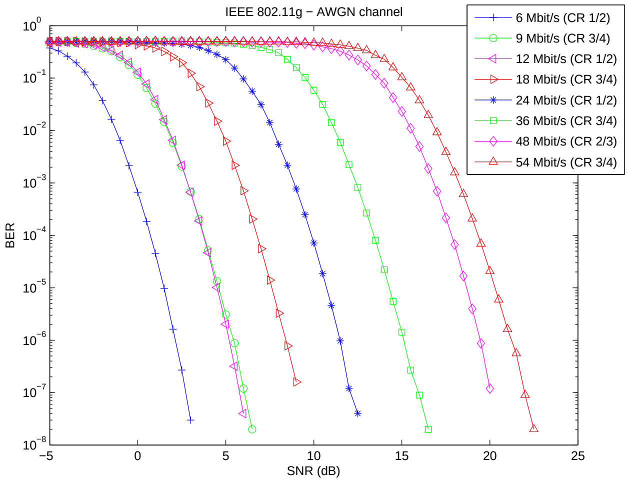


**Fig. 18.** Transmission of IEEE 802.11g over AWGN channel.

## 6. Conclusion

In this paper the IEEE 802.11b/g and Bluetooth 2.1 EDR (non AFH) physical layer model in Mathworks Matlab Simulink has been provided. As a main result from simulations, IEEE 802.11g standard provides the best performance when mandatory data rates (non-punctured convolutional codes) are used. Also Bluetooth EDR 3 Mbit/s causes smaller interference to the IEEE 802.11b signal than Bluetooth 1 Mbit/s data rate.

Bluetooth and Wi-Fi (IEEE 802.11b/g) physical layer models were based on the demo models available at [4] and extended with 2 and 3 Mbit/s (Bluetooth) and extended with IEEE 802.11g specification. All simulations have been made in baseband and for at least $10^8$ transmitted bits or minimum of 100 errors. Graphical results are commented in the text of the paper. The spectrum of the simulation is compared with the measured spectrum in Fig. 13.

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