Suppression of Bluetooth Interference on OFDM in the 2.4 GHz ISM Band

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Abstract— **In the presented paper, two new methods for blind detection and suppression of Bluetooth (BT) interference in case of an OFDM-based transmission system according to the novel WLAN standard IEEE 802.11g are proposed. While the first method searches for abrupt power changes of the received symbols by differentiation in frequency direction, the second approach makes use of the median filtering, which is well known from the digital image processing. After detection, the influence of the BT interference is suppressed by modifying the values of the affected soft-decision demodulated bits at the input of the channel decoder. Especially for the PSK-modulated modes of IEEE 802.11g, this leads to a significant improvement of the frame error rate, as we will show in our simulation results.**

Index Terms— **OFDM, IEEE 802.11g, Bluetooth interference**

I. Introduction

The physical layer (PHY) part of the novel WLAN standard IEEE 802.11g comprises different transmission techniques in the 2.4 GHz ISM (industrial, scientific, and medical) band, e.g. direct sequence spread spectrum (DSSS) and complementary code keying (CCK) according to the IEEE standard 802.11b, as well as OFDM-based transmission analog to IEEE 802.11a. The coexistence of DSSS and OFDM modes are assured by the requirement, that the clear channel assessment (CCA) mechanism of a 802.11g device must be able to detect a "medium busy" condition for all data rates and modulations of IEEE 802.11g. However, severe interference problems with other standards using the ISM band, especially Bluetooth, can occur [4].

The impact of BT interference on the performance of an IEEE 802.11b transmission system, i.e. DSSS, has already been investigated plurally, e.g. [5],[6], and [7]. For this reason, this paper focusses on the performance degradation of the OFDM mode of IEEE802.11g. In that case, the frequency hopping, narrow band BT signal can be interpreted as randomly occurring partial band jamming of the OFDM spectrum. The receiver may not be able to recover the information transmitted on the affected subcarriers, so that the corresponding soft-decision demodulated values at the input of the channel decoder are erroneous. Unfortunately, due to the increased input power at the affected subchannels, caused by the superposition with the interfering signal, these erroneous values have a high magnitude, thus the channel decoder wrongly treats them as highly reliable.

The magnitude correction of the affected soft information represents an effective countermeasure, but therefore the presence and frequency position of BT interference has to be accurately estimated. For this purpose, we propose two new blind detection algorithms. Especially in case of BPSK or QPSK modulated subcarriers these algorithms emerge as very reliable as we will show in our simulation results.

The paper is organized as follows: Section II deals with the description of the coexistence scenario and the impact of BT interference on the OFDM transmission. In section III we present our new blind BT detection algorithms as well as the interference suppression based on the modification of the soft-decision demodulated bits at the input of the channel decoder. Section IV comprises the simulation results followed by a conclusion of the paper in section V.

II. COEXISTENCE SCENARIO

The ISM band comprises the frequency range from 2400 to 2483.5 MHz. Within this band, in case of the non-overlapping channel selection there are three channels for the OFDM modes of IEEE802.11g, each with a signal bandwidth of 20 MHz [1]. 48 of the 64 subcarriers with a spacing of $\Delta f = 312.5\,\text{kHz}$ are used for data and 4 for pilot information. The duration of an OFDM symbol is $4\,\mu$s including a cyclic prefix of $0.8\,\mu$s. Multiple OFDM symbols are combined to a physical layer convergence protocol (PLCP) frame [2] comprising a preamble, header, and data part.

Bluetooth divides the ISM band into 79 radio frequency (RF) channels, each 1 MHz broad, hopping from one to another according to a pseudo random sequence. In case of data transmission a BT packet can comprise one, three, or five slots of duration $T_{bs} = 625\,\mu$s and ends with a kind of guard period of $T_{bp} - T_{bt} = 259\,\mu$s, where T_{bt} is the active transmission time and $T_{bp} = \alpha \cdot T_{bs}$, $\alpha \in \{1, 3, 5\}$, the overall duration of the BT packet over which one RF channel remains established.

In case of a BT system under full load, the collision probability between a PLCP frame and a BT packet can easily be calculated in dependency of the PLCP frame duration T_o [5]. Regarding time, the minimum and maximum number of BT packets overlapping the PLCP frame are

$$N_1 = \left\lceil \frac{T_o - (T_{bp} - T_{bt})}{T_{bp}} \right\rceil ; \quad N_2 = N_1 + 1 \,. \qquad (1)$$

If for the relative delay τ between the start of a BT packet and a PLCP frame applies $\tau_1 - T_{bt} \leq \tau \leq \tau_1$ with

$$\tau_1 = \left\lceil \frac{T_o}{T_{bp}} \right\rceil \cdot T_{bp} - T_o \qquad (2)$$

then N_1 BT packets overlap with the PLCP frame, otherwise N_2. Assuming τ to be equally distributed in the interval $[0, T_{bp}]$ the probability of occurrence of N_1 and N_2 can be formulated as

$$P_1 = \left(\frac{\tau_1 - T_{bt}}{T_{bp}} \right) \bmod 1 \qquad (3)$$

and

$$P_2 = \left(\frac{T_{bt} - \tau_1}{T_{bp}} \right) \bmod 1 \,. \qquad (4)$$

The probability for a BT packet being located within the frequency band of the OFDM system is

$$P_f = \frac{B_o}{B_{bc} \cdot N_{bc}} \qquad (5)$$

with B_o as the bandwidth of the OFDM system as well as B_{bc} and N_{bc} as the bandwidth and number of the BT RF-channels, respectively. Combining (3), (4), and (5) we can write the probability of a collision between a PLCP frame and BT packets as follows:

$$P_c = 1 - \left[P_1 \cdot (1 - P_f)^{N_1} + P_2 \cdot (1 - P_f)^{N_2} \right] \qquad (6)$$

In Fig. 1, the collision probability according to (6) is plotted in dependence of the PLCP frame length, assuming a BT transmission under full load with single- or multi-slot packets. In the following, we consider the case of single-slot packets, which comprise an active transmission time per packet of $T_{bt} = 366\,\mu s$, corresponding to the period of approx. 93 OFDM symbols, each with a duration of $4\,\mu s$.

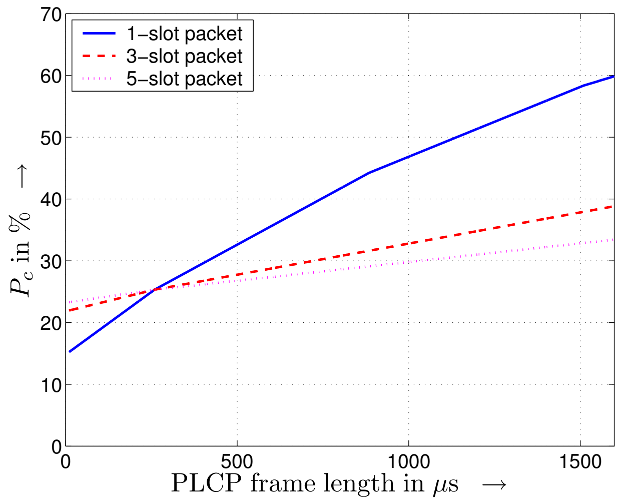

Fig. 1. Probability of collision with BT packet

The BT signal is characterized by Gaussian frequency shift keying (GFSK) modulation with a time-bandwidth product $B{\cdot}T = 0.5$ and a modulation index $\eta = 0.28 \ldots 0.35$. The resulting normalized power density spectrum is illustrated in Fig. 2. The mainly interfering part can be seen in the power range from 0 to -20 dBr and has a bandwidth of approx. 1 MHz. This corresponds to the bandwidth of three adjacent subchannels of the OFDM system which consequently are mostly affected by the interference. Nevertheless, it is important to note, that the impact on the remaining subcarriers can't be neglected due to the leakage effect, which is a consequence of the BT carrier not matching the subcarrier frequency pattern of the OFDM system, as will be shown in the following.

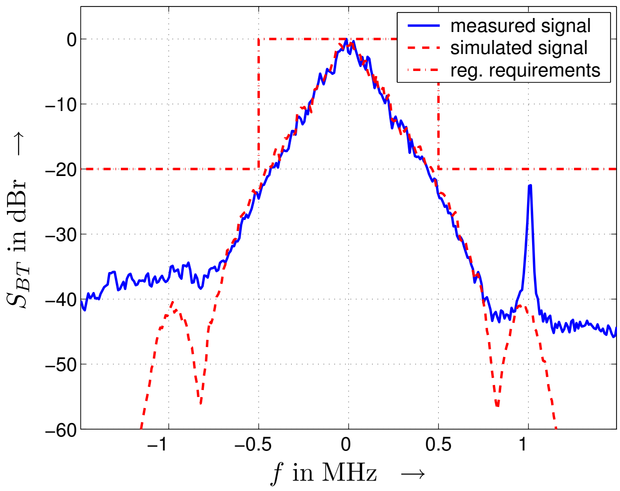

Fig. 2. Measured and simulated power density spectrum of a BT signal (one RF channel)

III. Detection and Suppression of BT Interference

The starting point of the proposed detection algorithms is the $(N \times M)$-matrix

$$\mathbf{R} = \begin{bmatrix} \hat{d}_0(i_0-M+1) & \cdots & \hat{d}_0(i_0) \\ \vdots & \ddots & \vdots \\ \hat{d}_{N-1}(i_0-M+1) & \cdots & \hat{d}_{N-1}(i_0) \end{bmatrix} \quad (7)$$

containing the M received symbols $\hat{d}_n(i)$ on each subcarrier with index $n = 0 \ldots N-1$, belonging to one frame, up to the time i_0. Taking the absolute value of the elements leads to the matrix $\mathbf{ABS}(\mathbf{R})$ containing the magnitudes of the received symbols.

For illustration, in Fig. 3 an example of a received PLCP frame affected by BT interference is plotted for different signal-to-interference ratios (SIR). The x-axis represents the frequency direction, i.e. the columns of $\mathbf{ABS}(\mathbf{R})$, while the time direction, i.e. the rows of $\mathbf{ABS}(\mathbf{R})$, is included by overlapping the sequent OFDM symbols. In the example, one can easily recognize the influence of the frequency selective channel as well as the geometric structure of the QPSK modulated symbols. Furthermore, the example shows that with a detection scheme based on the magnitudes of the received signal only, it is very complicated to detect a BT interferer in case of an SIR of 20 dB and above, because its influence is hardly to distinguish from that of the frequency selective channel. On the other hand, in case of an SIR of 0 dB or below, the BT interferer can be easily detected, but as a consequence of the leakage effect, the severe distortions of many subcarriers make it almost impossible to correctly exploit the OFDM symbols.

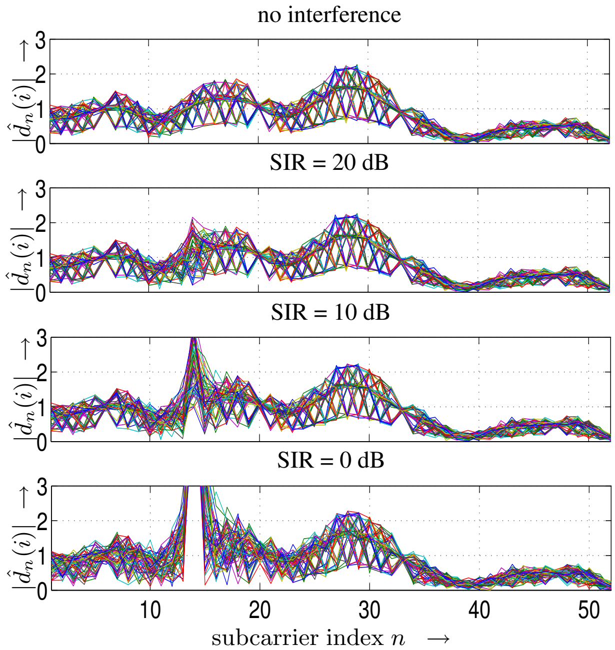

Fig. 3. Examples of received OFDM symbols affected by BT interference of different power

A. *Differentiation in frequency direction*

The first detection algorithm starts by twice calculating the difference quotient in column direction of $\mathbf{ABS}(\mathbf{R})$, which represents an approximation of a twofold differentiation of the symbol magnitudes in frequency direction:

$$\mathbf{R}'' = \mathbf{\Phi}' \cdot \mathbf{R}' = \mathbf{\Phi}_{[1:N-2,1:N]} \cdot \mathbf{\Phi} \cdot \mathbf{ABS}(\mathbf{R}) \quad (8)$$

with the $(N-1 \times N)$-matrix

$$\mathbf{\Phi} = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 & -1 \end{bmatrix} \quad (9)$$

and $\mathbf{\Phi}'$ as $\mathbf{\Phi}$ reduced by the last row.

The algorithm then acquires the indices of the elements of $\mathbf{R}''$, whose value is greater than an adaptive, e.g. depending on the mean receive power, relative threshold β:

$$\Gamma_n = \left\{ m \,|\, \mathbf{R}''_{[n,m]} \geq \beta \right\} \quad (10)$$

Afterwards, each subcarrier n is checked for the maximum number of subsequent elements in Γ_n. If this number exceeds a predefined value the subcarrier is assumed to be affected by BT interference.

B. Median filtering

Our second method is based on the median filter mainly used in image processing for reducing the pixel noise without significantly blurring the edges. The median filter outputs the value that is the median of the actual filter window, i.e. after sorting the values of the filter window by magnitude, the middle value is selected. For the presented detection algorithm a one-dimensional filter window sliding in time direction over all yet received OFDM symbols is used.

The initial step is performing a median filtering in row direction over the elements of $\mathbf{R}$. Thereby, the variance of the symbol magnitudes, due to noise influences and the signal constellation of the applied modulation scheme itself, is reduced in time direction, see an example in Fig. 4. A subsequent correlation with an appropriate vector, e.g. $\delta = [+1, +1, -1, -1]$, in column direction is used for emphasizing the slopes of increased symbol magnitudes in frequency direction. Finally, performing a second median filtering in row direction and then averaging over time, i.e. calculating the mean value in row direction, we determine a value γ_n for each subcarrier, see Fig. 5, which we compare with a predefined threshold. Based on this criterion, we decide whether a subcarrier is affected by BT interference or not. As we verified by Matlab simulations, in case of an OFDM receiver with two or more receive antennas, the reliability of the above presented methods is significantly improved by applying maximum ratio combining (MRC) of the received symbols.

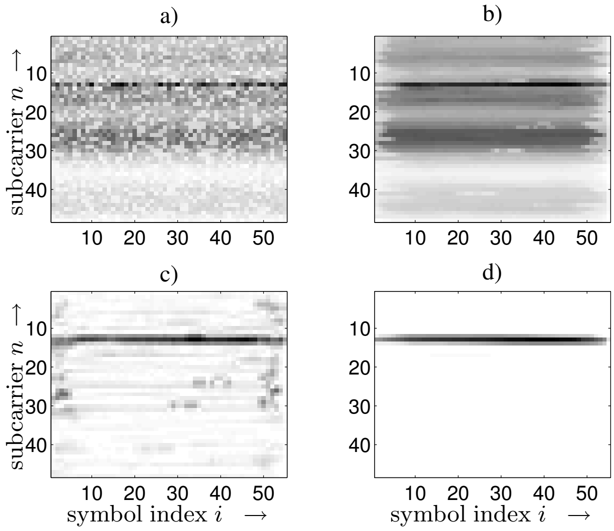

Fig. 4. a) received symbols, b) after 1st median filtering, c) after correlation, d) after 2nd median filtering

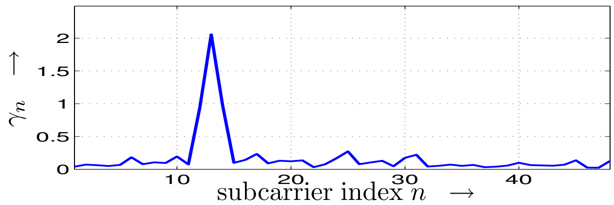

Fig. 5. Resulting values after twofold median filtering and time averaging

C. Interference suppression

After the presence and frequency position of BT interference has been detected, the interference influence can be suppressed by a straightforward approach letting the channel decoder "do the work": After a soft-decision demodulation and demapping of the receive symbols we obtain bits weighted with reliability information, in the following called soft-bits, which are exploited by the channel decoder. If we know the position of the BT interferer, we reduce the magnitudes of the soft-bits belonging to the affected and its adjacent subcarriers by an appropriate scheme. Thus, these soft-bits are classified as less reliable in the subsequent channel decoding process.

The optimum solution would be the weighting of each soft-bit with the SIR of the corresponding subcarrier. But therefore a reliable and accurate estimation of the SIR becomes necessary, which is hardly to achieve with the presented detection algorithms. However, by simulations we ascertained that a fixed sequence of appropriate weighting factors, where the magnitudes of the soft-bits according to the nine most affected subcarriers are reduced, worked well in most cases.

IV. Simulation results

A performance comparison of the proposed algorithms can be seen in Fig. 6. The presented frame error rates (FER) were obtained by simulating the transmission of 10000 PLCP frames, consisting of 54 OFDM symbols, for each 2-dB step of the E_b/N_0 ratio. The modulation scheme on each subcarrier was QPSK, according to the 12-Mbit/s mode of IEEE 802.11a. For each frame, one transmission channel was randomly created in compliance with the HIPERLAN/B model defined in [9]. In case of the simulations including BT interference, the SIR was set to 0 dB and the collision probability realized according to (6). The interfering signal was simulated by modelling a BT transmitter in time domain in order to include all the influences of the before mentioned leakage effect.

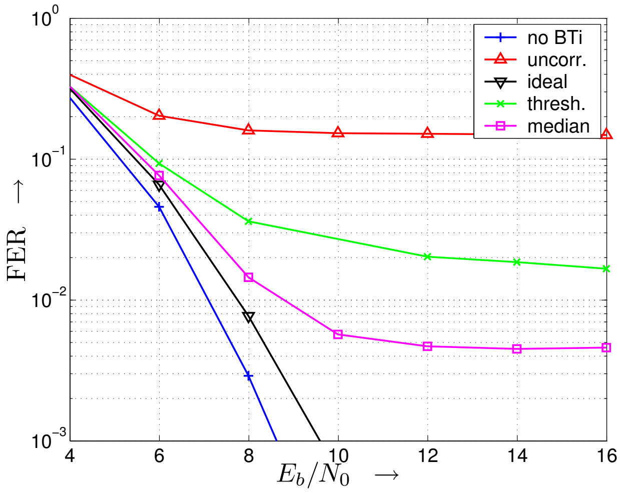

Fig. 6. Frame error rate of the 12 Mbit/s OFDM mode (QPSK) in case of BT interference with $\mathrm{SIR} = 0\,\mathrm{dB}$

The upper curve ('uncorr.') represents the case of unsuppressed BT interference, where it is obvious that due to the high error floor at a FER of $1.5 \cdot 10^{-1}$ the transmission performance of the OFDM system is severely declined compared to the interference-free case ('no BTi'). With interference suppression based on the first detection method ('thresh.'), the FER is reduced by almost a factor of 10. The second detection method ('median') performed even better: Although still showing an error floor, a FER of $4.5 \cdot 10^{-3}$ is reached. For reference, the FER resulting from a suppression based on the ideal knowledge of the BT interferer position ('ideal') is also plotted to demonstrate the maximum achievable gain in case of perfect interference detection and the proposed suppression method.

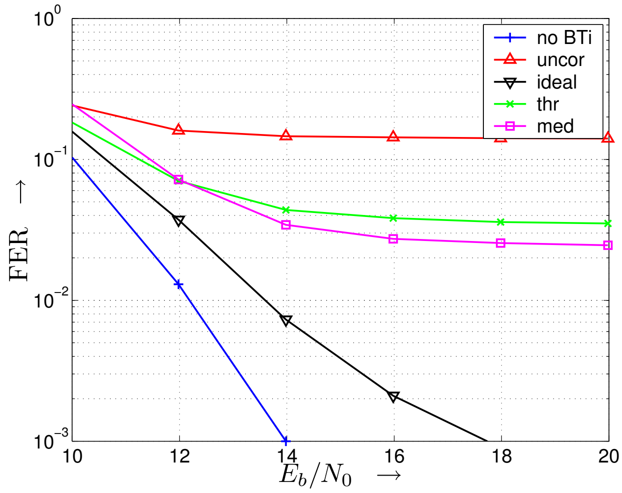

Fig. 7. Frame error rate of the 36 Mbit/s OFDM mode (16-QAM) in case of BT interference with $\mathrm{SIR} = 10\,\mathrm{dB}$

In Fig. 7 the simulated FERs for the 36-Mbit/s mode, i.e. 16-QAM modulated subcarriers, and a SIR of 10 dB are plotted. While in the case of unsuppressed interference the FER still shows an error floor at $1.5 \cdot 10^{-1}$, the gain of both detection method is less than in the 12-Mbit/s mode and leads to an error floor at $3 \cdot 10^{-2}$. The reason for this degradation is the increased variance of the signal amplitude due to the more complex signal constellation scheme: To avoid wrong decisions the thresholds of the detection algorithms have to be adjusted to lower values, resulting in a decreased sensitivity for the BT interference.

V. Conclusions

As shown by simulation results, BT interference with an SIR lower 20 dB leads to severe degradations of the FER of an OFDM system according to IEEE 802.11g, making it necessary to detect and suppress the interferer. Therefore, we presented two novel blind detection algorithms and a straightforward suppression approach. In case of QPSK modulated subcarriers a significant improvement of the FER can be realized with the application of the proposed median filter method, while for more complex signal constellation schemes, like 16-QAM, the maximum achievable gain is less but still noticeable.

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