Blind Bluetooth Interference Detection and Suppression for OFDM Transmission in the ISM Band

Sven Vogeler, Lars Broetje, and Karl-Dirk Kammeyer
University of Bremen, Department of Communications Engineering,
P.O. Box 33 04 40, D-28334 Bremen, Germany,
E-mail: {vogeler, broetje, kammeyer}@ant.uni-bremen.de
and
Reinhard Rueckriem, and Stefan Fechtel
Infineon Technologies AG,
P.O. Box 80 09 49, D-81609 Munich, Germany
E-mail: {reinhard.rueckriem, stefan.fechtel}@infineon.com

***Abstract*— The performance of an OFDM-based transmission system according to IEEE 802.11g can severely suffer from interfering Bluetooth packets. Therefore, we propose two new approaches for narrow-band interference suppression as countermeasure. At first, the presence and frequency position of interference is blindly estimated by evaluating either the magnitude variance of the received symbols or the noise power on each subchannel. For that purpose, we present one algorithm based on differentiation in frequency direction, and another one making use of the median filter. After detection, an interference suppression by modifying the softbit magnitudes at the input of the channel decoder leads to a significant improvement of the system performance, as we will show by simulations.**

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 an IEEE 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 (BT), 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 IEEE 802.11g. 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 (softbits) 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 blind detection algorithms.

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 softbit magnitudes. 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 IEEE 802.11g, 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 $4\,\mu\text{s}$ including a cyclic prefix of $0.8\,\mu\text{s}$. 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 $T_{bs} = 625\,\mu\text{s}$ 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

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

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

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

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

$$P_1 = \left(\frac{\tau_1 - T_{bt}}{T_{bp}} \right) \mathrm{mod}\, 1 \tag{3}$$

and

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

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

$$P_f = \frac{B_o}{B_{bc} \cdot N_{bc}} \tag{5}$$

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:

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

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 $4\,\mu s$.

The BT signal is characterized by Gaussian frequency shift keying (GFSK) modulation with a time-bandwidth product of $B{\cdot}T = 0.5$ and a modulation index $\eta = 0.28...0.35$. 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

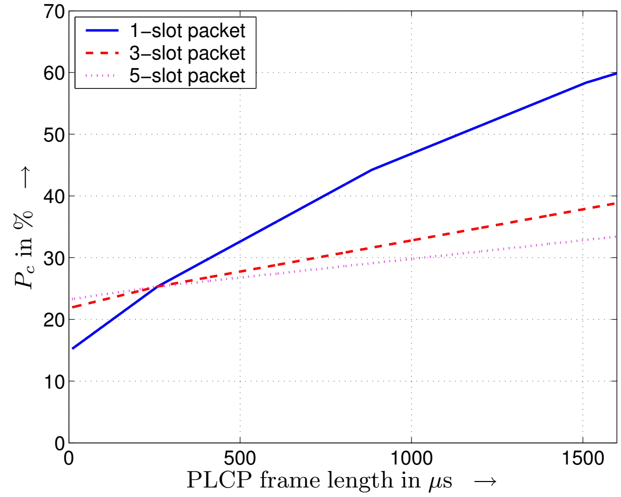

Fig. 1. Probability of a collision with a BT packet

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.

III. Detection and Suppression of BT Interference

The interference detection can be performed by evaluating either the magnitude variance of the received symbols, or the noise power on each subcarrier. In the first case, the input values of the proposed interference detection algorithms are obtained by an $(N \times M)$-matrix

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

containing the magnitudes of M received symbols $\hat{d}_n(i)$ (frequency domain) on each subcarrier with index $n = 0...N{-}1$.

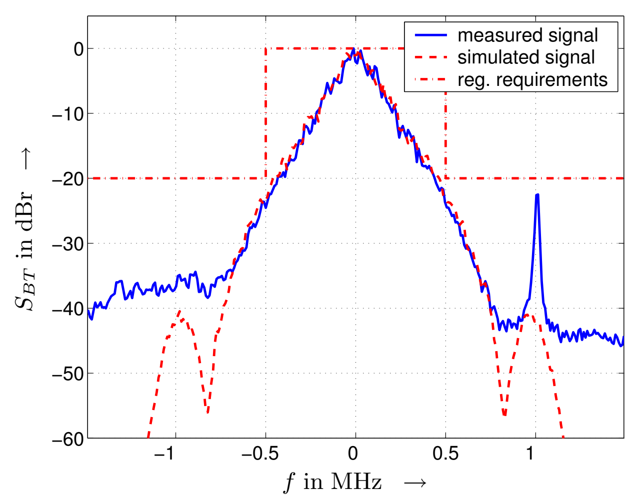

Fig. 2. Power density spectrum of a BT signal for one RF channel

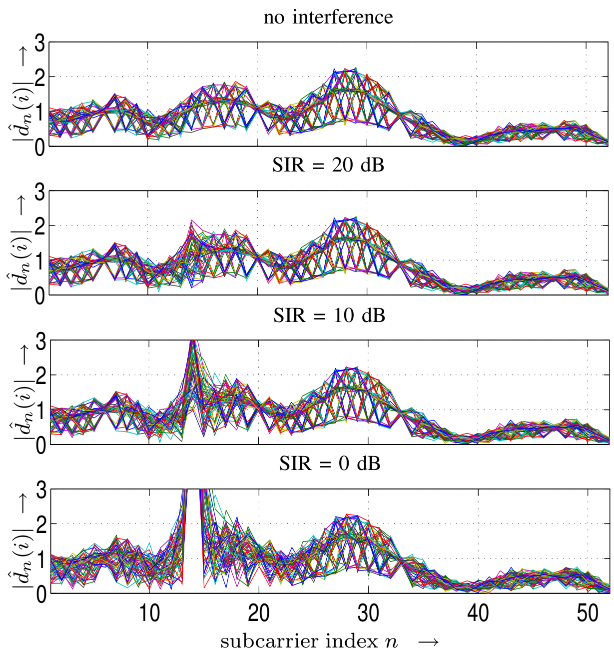

Fig. 3. Examples of received OFDM symbols affected by BT interference of different power

Thus, the matrix represents the block of the last M OFDM symbols up to the time index i_0, within the data part of one PLCP frame.

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 $\mathbf{R}$, while the time direction, i.e. the rows of $\mathbf{R}$, 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.

In case of a higher order modulation scheme (e.g. 16-QAM or 64-QAM), the interference detection based on the absolute values of the received symbols gets even more difficult, because the signal constellation itself results in a stronger variance of the symbol magnitudes. Then, the noise power on each subcarrier, as considered in [10], offers a more reliable decision criterion - accepting a higher computational effort. In order to estimate the noise influence on each subchannel, we calculate the Euclidean distance between the received, channel equalized signal constellation point and the most likely transmitted symbol, which for instance can be determined by simply selecting the closest symbol to the received constellation point.

Of course, a more reliable estimation of the most likely transmitted symbol can be realized with the help of the channel decoder. Therefore, we take a received constellation point, perform a soft demodulation followed by a channel decoding, as well as a recoding and remodulation, before we calculate the Euclidean distance between the resulting reference symbol $\tilde{d}_n(i)$ and the received constellation point:

$$\delta_n(i) = \left| \frac{1}{H_n} \cdot \hat{d}_n(i) - \tilde{d}_n(i) \right|^2 , \tag{8}$$

In contrast to (7), we now collect the distance information in the $(N \times M)$-matrix

$$\mathbf{R} = \begin{bmatrix} \delta_0(i_0-M+1) & \cdots & \delta_0(i_0) \\ \vdots & \ddots & \vdots \\ \delta_{N-1}(i_0-M+1) & \cdots & \delta_{N-1}(i_0) \end{bmatrix} , \tag{9}$$

which serves as an alternative input source for the detection algorithms described in the following. The choice of using either (7) or (9) is a compromise between reliability and computational effort and depends on the applied modulation scheme.

A. Differentiation in frequency direction

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

$$\mathbf{R}'' = \mathbf{\Phi}' \cdot \mathbf{R}' = \mathbf{\Phi}_{[1:N-2,1:N]} \cdot \mathbf{\Phi} \cdot \mathbf{R} \tag{10}$$

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

$$\mathbf{\Phi} = \begin{bmatrix} 1 & -1 & 0 & \cdots & 0 \\ 0 & 1 & -1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & 1 & -1 \end{bmatrix} \tag{11}$$

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:

$$\Gamma_n = \left\{ m \,|\, \mathbf{R}''_{[n,m]} \geq \beta \right\} \tag{12}$$

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 elements, due to channel noise influences and the signal constellation of the applied modulation scheme itself, is reduced in time direction. An example can be seen in Fig. 4. A subsequent correlation with an appropriate vector, e.g. $\xi = [+1, +1, -1, -1]$, in column direction is used for emphasizing the slopes of increased symbol magnitudes or noise values 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 verified with Matlab simulations, in case of an OFDM receiver connected to multiple receive antennas, the reliability of the above presented methods is significantly improved by applying maximum ratio combining (MRC) of the received symbols.

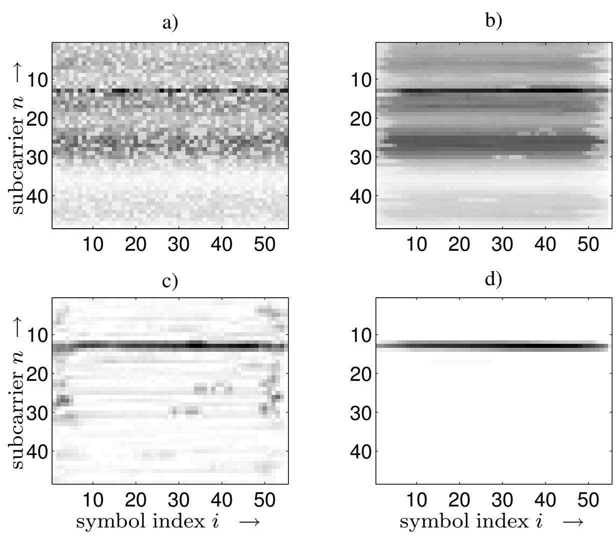

Fig. 4. a) received symbols, b) after 1st median filtering, c) after correlation, d) after 2nd median filtering

C. Detection in case of partially affected frames

If a PLCP frame is in time only partially affected by BT interference, the above described methods may not be able to detect this. By tracking the magnitudes of the received and equalized symbols over time, separately on each subcarrier, one can determine a sudden increase from one OFDM symbol

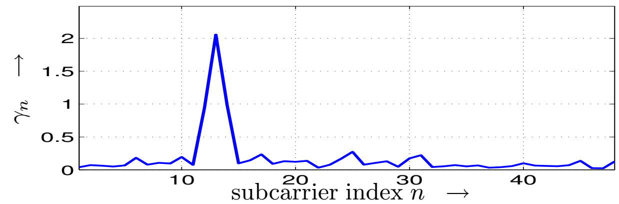

Fig. 5. Resulting values after twofold median filtering and time averaging

to the following at the beginning of an interfering BT packet and, the other way round, a sudden decrease at a packet's end. In the first case, only the affected part of the frame needs to be corrected, whereas in the second case, it has to be evaluated if the preamble of the PLCP frame has also been interfered by BT. This could have led to an incorrect estimation of the corresponding channel coefficient, thus all equalized symbols on this subchannel are probably erroneous and should be disregarded. Again, the reliability of detection can be significantly increased by applying a two-fold median filtering, analogical to the above described algorithm.

D. Interference suppression

Having estimated the presence and frequency position of BT interference, 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, called softbits, which are exploited by the channel decoder. If we know the position of the BT interferer, we reduce the magnitudes of the softbits belonging to the affected and its adjacent subcarriers by an appropriate scheme. Thus, these softbits are classified as less reliable in the subsequent channel decoding process.

The optimum solution would be the weighting of each softbit 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 softbits according to the nine most affected subcarriers are reduced, worked well in most cases.

IV. Simulation results

In Fig. 6, the frame error rates (FER) of an OFDM transmission with and without BT interference, as well as using different correction methods are plotted for a comparison of the presented algorithms. The results were obtained by simulating the transmission of 10000 PLCP frames, each comprising 54 OFDM symbols, for each 2-dB step of the E_b/N_0 ratio. The applied modulation scheme 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.

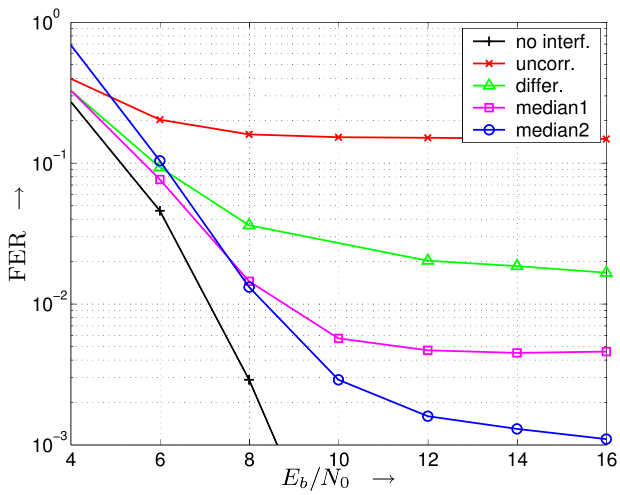

Fig. 6. Frame error rates for QPSK modulated subcarriers and 0 dB SIR

The upper curve ("uncorr.") illustrates that without applying any correction techniques, a reliable OFDM transmission is not possible at an SIR of 0 dB. With the help of the detection algorithm based on the two-fold convolution of the symbol magnitudes ("differ.") according to (7) the FER can be reduced by almost a factor of ten to the value $2 \cdot 10^{-2}$ at an E_b/N_0 of 12 dB and above. Much better results are obtained by applying the median filtering algorithm ("median1"), reaching a FER of below 10^{-2} at already 9 dB in E_b/N_0. The two-fold median filtering on the basis of the input matrix according to (9) shows the greatest performance ("median2"), reducing the FER to less than $2 \cdot 10^{-3}$ for an E_b/N_0 greater 11 dB. However, its main disadvantage can be seen in the high computational effort due to the included channel decoding process.

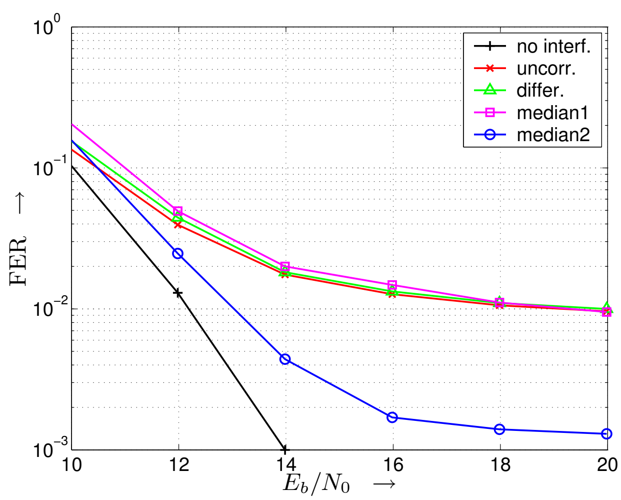

Fig. 7. Frame error rates for 16-QAM modulated subcarriers and 20 dB SIR

In Fig. 7 the simulated FERs for an OFDM transmission in the 36 Mbit/s mode, i.e. 16-QAM modulated symbols, are plotted to demonstrate the above mentioned detection problems estimating the BT interference based on changes in symbol magnitudes. Due to the magnitude variance caused by the higher order modulation scheme, the thresholds of the algorithms have to be fixed to a relatively high value in order to avoid wrong decisions. Consequently, the estimation process becomes too insensitive for an interference detection at an SIR of 20 dB or less. In that case, the usage of the noise power based values according to (9) in combination with the two-fold median filtering represent a well working solution, reducing the FER significantly.

V. Conclusions

In the presented paper, we showed that Bluetooth interference can severely degrade the performance of an OFDM-based transmission system according to the WLAN standard IEEE 802.11g. After a short description of the collision scenario, we proposed new blind approaches for estimating and suppressing the interference impact. As verified with simulation results, the presented algorithms can significantly improve the system performance. Especially the two-fold median filtering algorithm in combination with the consideration of the noise power on each subcarrier provides reliable estimation results, even for higher order modulation schemes, as demonstrated by simulations with 16-QAM modulation. The interference suppression itself is realized by a magnitude reduction of the softbits according to the affected subchannels, thus these are treated as less reliable in the channel decoding process.

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