Channel selection requirements for Bluetooth receivers using a simple demodulation algorithm

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Abstract—**In our *Software Defined Radio* (SDR) project we combine two different types of standards, Bluetooth and HiperLAN/2, on one common hardware platform. SDR system research aims at the design, implementation and deployment of flexible radio systems that are re-programmable and re-configurable by software.**

Goal of our project is to generate knowledge about designing the front end of an SDR system (from the antenna signal to the channel bit stream) where especially an approach from *both* analog and digital perspective is essential.

This paper discusses the channel selection requirements for the Bluetooth standard. The standard specifications specify only the power level of the interferers, the power level of the wanted signal and the maximum allowed Bit Error Rate (BER). In order to build a radio front-end, one has to know the required (channel) suppression of these interferers.

From [1] it is known that the required SNR for a Bluetooth demodulator is 21 dB, but by which value should interferers be suppressed? This paper will validate if the SNR value needs to be used for the suppression of adjacent channels. In order to answer this question a simulation model of a Bluetooth radio front-end is built.

Keywords— **Software-Defined radio (SDR), Bluetooth, channel selection requirements.**

I. INTRODUCTION

A SDR (Software-Defined Radio) system is a flexible radio system that is re-programmable and re-configurable by software in order to cope with a multi-service[1], multi-standard and multi-band environment [2].

In our SDR project [3] we integrate two different types of standards, HiperLAN/2 and Bluetooth on one common hardware platform. The focus of our project is on designing the front end of a receiver (from antenna to demodulation in bits) of an SDR system for a mobile terminal. Furthermore, this SDR design should be feasible within a few years. So power consumption is an important issue.

The vehicle of our project is a notebook which we add the SDR functionality. This has three advantages. First, we can use the processing capabilities of the general purpose processor for digital signal processing. Second, in comparison to SDR for mobile phones, our demonstrator can consume much more power (in the order of 1 W). Third, a notebook is very suited for demonstration purposes.

Bluetooth and HiperLAN/2 are different types of standards. Bluetooth is a low-cost, low-speed Personal Area Network (PAN) standard [4] , using GFSK modulation. Typical applications are replacements of cables, e.g. wireless headsets, keyboards, . . .). HiperLAN/2 on the other hand is a high-speed Wireless LAN (WLAN) standard (e.g. [5] and [6]), using OFDM as modulation technique.

As HiperLAN/2 requires more processing power than the Bluetooth standard, we chose to use the HiperLAN/2 hardware to implement a Bluetooth receiver. So, whereas most commercial Bluetooth chips are low-cost and inflexible, in our project flexibility and re-use of hardware is important. It is for that reason that a part of the channel selection and demodulation will be done in the digital domain.

This paper discusses the channel selection requirements for Bluetooth receivers. The question is: How strong must the neighboring channel be suppressed in order to meet the maximum allowed BER of 0.1 % [4]? A simple answer can be made by assuming that all interferers have to be suppressed 3 dB below the minimum required SNR for a BER of 0.1 %. This paper will verify this assumption. On the other hand, these requirements depend for a large part on the complexity of the demodulation algorithms of the receiver:

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[1] With a *multi-service system* we mean a system that is able to handle different types of data traffic: different with respect to content (email,web,audio,video,speech, . . .), different with respect to traffic patterns and different with respect to Quality of Service (QoS) requirements.

simple demodulation algorithms are expected to be more sensitive to noise than more complex algorithms.

So another research question is: what is the minimum required SNR (for a maximum BER of 10^{-3}) for a demodulation method? Does this value match the value found in [1]? As it is expected that a more complex demodulation algorithm lowers the channel selection requirements, we are interested in the optimal demodulation algorithm which has the lowest required SNR.

Due to time constraints, this paper will only discuss one implementation of the FM-to-AM-conversion method [7], which is a non-coherent or a-synchronous detection method.

First, this paper will discuss the Gaussian Frequency Shift Keying (GFSK) modulation and some of its properties. Then, the FM-to-AM-conversion method will be discussed. A model of an implementation of an FM-to-AM-conversion method will be used in experiments to derive for this type of demodulator its channel selection requirements. Finally, conclusions will be drawn.

II. GFSK MODULATION

In normal continuous FSK a '0' is represented by an harmonic signal with frequency f_0 and a '1' by frequency f_1, both per interval of T s. Continuous FSK uses an Voltage-Controlled Oscillator (VCO) that is driven by the bit signal. In this implementation no phase shifts occur between bit transitions, which explains the name continuous FSK. However due to the binary nature of the input signal, higher harmonics appear in the output signal and therefore results in a large bandwidth. It is for that reason that GFSK uses a Gaussian pre-modulation filter.

Fig. 1 shows a GFSK modulator. First the bits are converted to signal elements. A '0' is being represented by a signal with value -1 and a '1' by a signal with value 1, each with a duration of T seconds. The filter output is then connected to an VCO that translates the amplitude of the filtered bits into an frequency shift. In Fig. 2, the effect of the Gaussian filter is shown. The Gaussian filter reduces the bandwidth of the input signal of the VCO. This reduces also the bandwidth of the output signal and therefore GFSK is more spectrum efficient compared to normal Frequency Shift Keying (FSK) at the cost of an increased BER [8].

For a normal (orthogonal) FSK signal in an Additive White Gaussian Noise (AWGN) channel the required SNR for a BER of 0.1% is about 11 dB [9]

Fig. 1. GFSK modulator

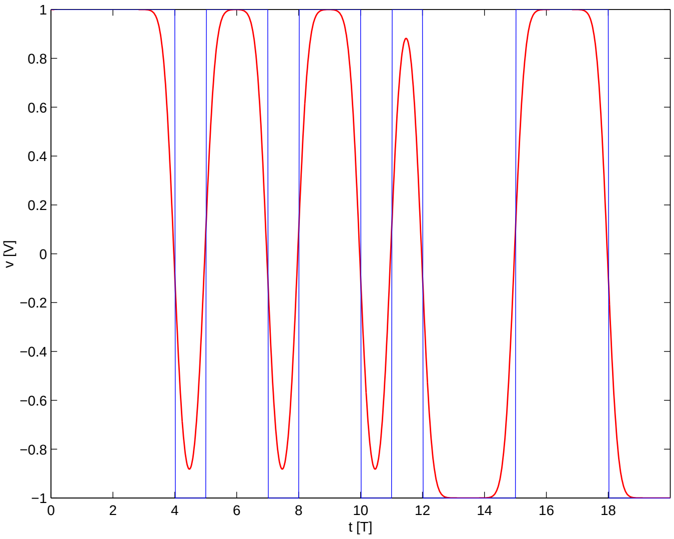

Fig. 2. Time signal before and after the Gaussian filter

(non-coherent receiver and hard decision each symbol time). The Gaussian pre-modulation filter, however, removes higher frequencies of the modulating signal (as can be seen in Fig. 2). This reduces the bandwidth of the VCO output signal but also reduces the *bit energy* which has a negative effect on the BER. In our literature search for GFSK demodulation we did not find a relation between the BER and SNR reported. However most designers use 21 dB [1] in order to meet a BER of 0.1%.

In Bluetooth systems, the modulation index h may vary between 0.28 and 0.35 [4]. The modulation index h is defined as:

$$h = \frac{2f_d}{R} = 2f_dT \qquad (1)$$

where f_d is the digital frequency deviation, R the bitrate and T the symbol time [10]. The frequency deviation (f_d) is the maximum frequency shift with respect to the carrier frequency, if a '0' or '1' is being transmitted.

For Bluetooth signals f_d may vary between 0.140 and 0.175 MHz (according to (Eq. 1)). Fig. 3 shows the power spectrum of a Bluetooth signal at 2 MHz with an $f_d = 0.175$ and Fig. 4 shows the power spectrum for $f_d = 0.140$. As expected, the power spectrum of Fig. 3 is a little wider and more flat than the one of Fig. 4. Visual inspection of both figures shows that the signal strength has dropped about 40 dB at the

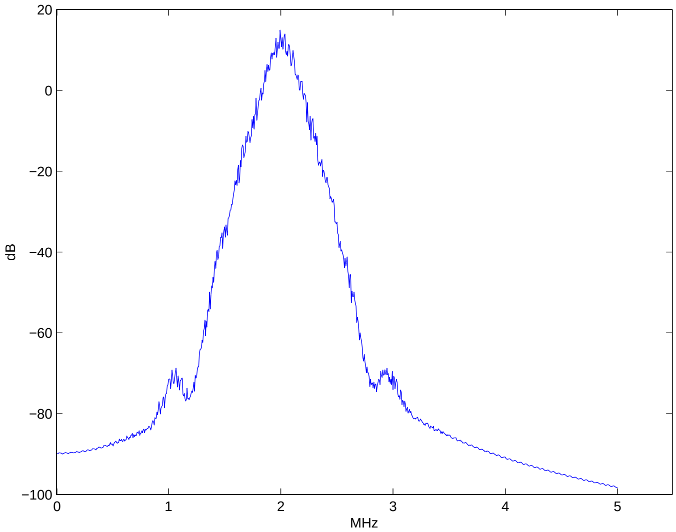

Fig. 3. Power spectrum of a GFSK signal with $f_d = 0.175$

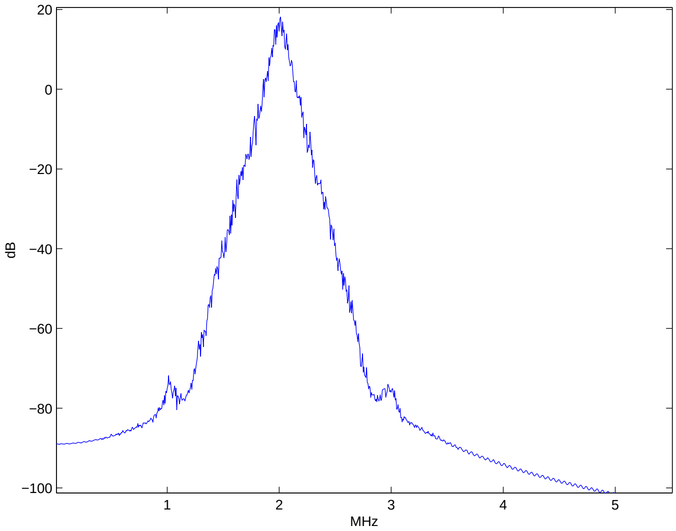

Fig. 4. Power spectrum of a GFSK signal with $f_d = 0.140$

border of the channel (channel spacing = 1 MHz [4]). Due to the relative small modulation index of Bluetooth GFSK, the signal energy is concentrated in a small band.

Fig. 5 shows the power spectrum of two neighboring channel (one with center frequency 2 MHz and the other at 3 MHz) for $f_d = 0.175$. As expected, visual inspection of the curve shows that both channels are very well separated, although a lower f_d (see Fig. 6) results in lower co-channel interference.

III. GFSK DEMODULATOR TYPES

According to Carlson [7], FSK demodulation algorithms can be divided into 4 types:

- FM-to-AM conversion, also called FM discriminator
- Phase-shift discrimination

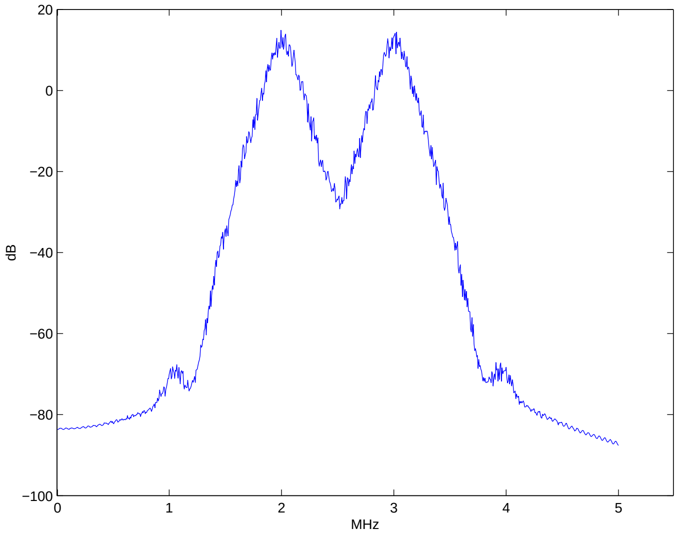

Fig. 5. Power spectrum of a two neighboring GFSK channels with $f_d = 0.175$

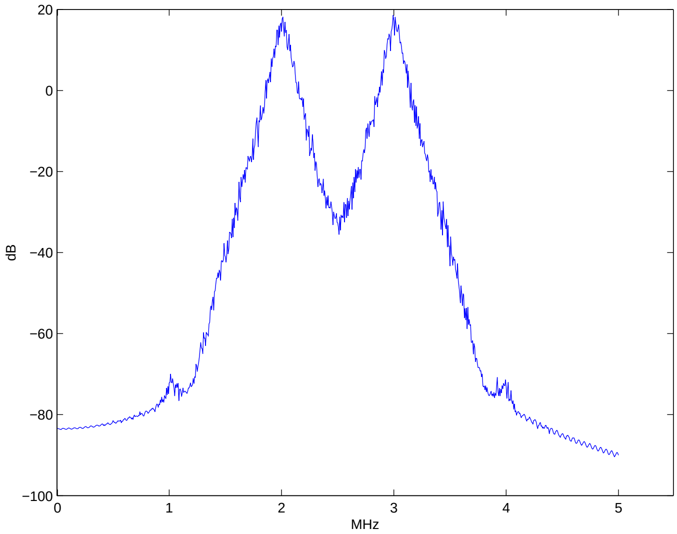

Fig. 6. Power spectrum of a two neighboring GFSK channels with $f_d = 0.140$

- Zero-crossing detection
- Frequency feedback

According to [11], the FM-to-AM conversion or FM discriminator allows the implementation for low-cost radio units, which is essential for Bluetooth units. It seems therefore appropriate to research the "cheapest" demodulator algorithm first.

A. FM-to-AM conversion

Goal of the FM-to-AM-conversion method is to translate a frequency shift into a amplitude change. A possible implementation is to use a time-delayed version of the incoming (low-IF) signal, see Fig. 8. This time-delayed signal is multiplied with the origi-

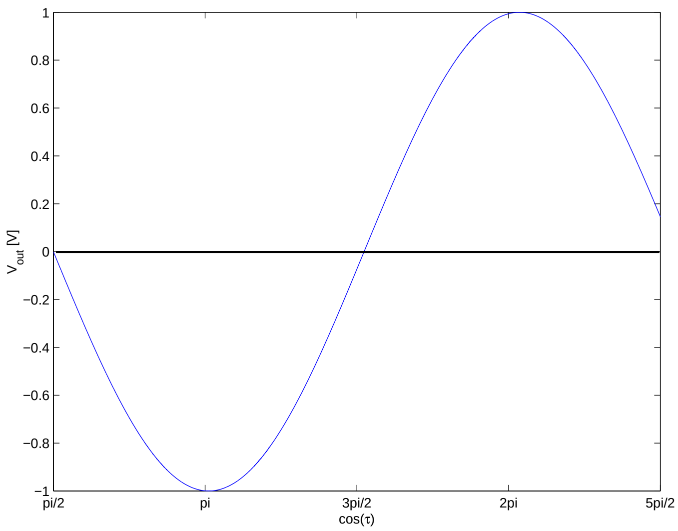

Fig. 7. Output of the FM-to-AM-converter block

nal, (not time-delayed) signal. The output of the FM-to-AM-conversion block with time delay τ depends on phase ($\phi(\tau)$), which is the phase difference between the original and time-delayed signal:

$$\begin{aligned} V_{out} &= \cos(2\pi f + \theta) * \cos(2\pi f + \theta + \phi(\tau)) \qquad (2) \\ &= \frac{1}{2}(\cos(\phi(\tau)) + \cos(4\pi f + 2\theta + \phi(\tau)))[V] \end{aligned}$$

If an integrate-and-dump part is used after the FM-to-AM-conversion block (see Fig. 9), the second term is assumed to be eliminated. So the output depends solely on τ. The time delay τ is chosen in such a manner that it will produce, in a noiseless situation, a phase shift of π for $f_0 = f_c - f_d$ and 2π for $f_1 = f_c + f_d$ (f_c is the central frequency). So, the output of this block will be -1 for a transmitted ’0’ and 1 for a transmitted ’1’. In Fig. 7 the relation between the phase shift and the output of the FM-to-AM-conversion block is shown. As expected the output for the central frequency (f_c) (phase shift of $\frac{3\pi}{2}$) is zero.

For Bluetooth signals the modulation index may vary between 0.28 and 0.35 [4]. For our experiments we use the middle of the two values: $h = 0.315$. The frequency deviation f_d is then according to Eq. (1), 0.1575. So, we want a phase shift of 2π for f_1, so the time delay must be:

$$\tau = \frac{1}{f_1} \qquad (3)$$

Furthermore, we want a phase shift of π for f_0. In this case the time delay must equal half the period time:

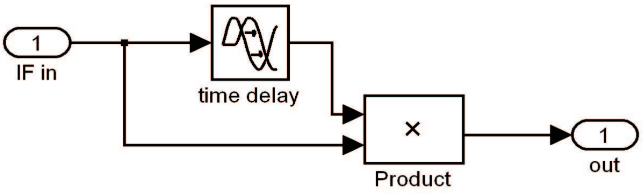

Fig. 8. FM-to-AM-conversion block with time delay τ

$$\tau = \frac{1}{2 f_0} \qquad (4)$$

From Eq. (3) and Eq. (4) the relation between f_0 and f_1 can be deduced:

$$f_1 = 2 f_0 \qquad (5)$$

Furthermore the the frequency difference between f_1 and f_0 is (according to Eq. (1)):

$$\Delta f = 2 f_d \qquad (6)$$

As $f_d = 0.1575$, according to Eq. (6), $\Delta f = 0.315$ MHz. So $f_0 = 0.315$ MHz and $f_1 = 0.630$ MHz. The carrier frequency is in this case $\frac{0.315+0.630}{2} = 0.4725$ MHz. Earlier stages of the receiver must translate the wanted channel to this center frequency! However, if the bandwidth of the signal is wider than 2 times the central frequency we cannot use this central frequency. A solution would be to give f_0 a phase shift of 2π and f_1 a phase shift of $\frac{3\pi}{2}$. In this case f_0 should be 0.630 MHz and f_1 0.945 MHz.

IV. EXPERIMENTS

In Simulink [12] we have built an FSK transmitter, AWGN channel, receiver (which uses the FM-to-AM conversion method) and a BER tester (see Fig. 9). The receiver consists of two parts apart from a pre-detection filter, the FM-to-AM conversion and an integrate-and-dump part. The latter part integrates over one symbol period (so T seconds). If the output is larger than zero, a ’1’ has been detected, lower than zero means a ’0’. A BER tester has been implemented which compares the transmitted bits with the received ones. It should be noted that the transmitted bits are generated by a random generator.

A. Verification of the simulation model

Before we can run any tests for Bluetooth GFSK signals, we validate our simulation model. This is accomplished by four experiments. In our first experiment an Minimum-Shift Keying (MSK) signal is

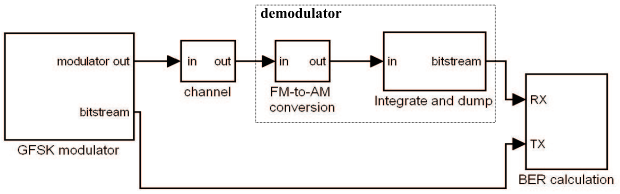

Fig. 9. Simulation model

	h	pre-det. filter passband[MHz]
MSK	0.5	$0 < passband < 1.5$
GMSK	0.5	$0.15 < passband < 1.375$
FSK	h = 0.315	$0.2075 < passband < 1.3675$
GFSK	h =0.315	$0.2625 < passband < 1.3125$

TABLE I
PRE-DETECTION FILTER PARAMETERS

used. In this case, the relation between SNR and BER is known [13], so we can verify our model. Experiment 2 consists of a Gaussian MSK (GMSK) signal with a Gaussian filter with $BT = 0.5$. Goal of this experiment is to research the influence of the Gaussian filter on the performance of our implementation of the FM-to-AM-conversion method.

The third experiment for verification is an FSK signal with modulation index equal to 0.315. The resulting FSK signal is non-orthogonal. Bluetooth GFSK uses also an modulation index between 0.28 and 0.35. Our final test is a Bluetooth GFSK signal with modulation index equal to 0.315 and a Gaussian filter with $BT = 0.5$. It should be noted that all experiments have been carried out with a pre-detection filter tailored for each modulation type. This pre-detection filter is designed is such a way that it passes 99% of the signal power. Table I shows the characteristics of the digital 256-order pre-detection FIR filters[2]. In our *digital* implementation we have chosen to use a sampling rate of 50 MHz. In experiment 1 and 2, the central frequency (f_c)is located at 0.75 MHz. In this case $f_0 = 0.5$ MHz and $f_1 = 1.0$ MHz. By setting the time delay to 1μs, the output of the FM-to-AM-conversion block is for f_0, -1 and for f_1 1.

However in experiment 3 and 4 we have chosen to use 0.7875 MHz and not 0.4725 MHz as carrier frequency. The bandwidth of the wanted signal is too large compared to the latter carrier frequency: a small part of power spectrum will exceed the 0 Hz line. For that reason we choose to use a carrier frequency of 0.7875 MHz. The delay, τ is set to 1.587 μs. This delay will cause an phase shift of 2π for f_0 and 3π for f_1. De original bits are retrieved by using a gain of '-1' after the FM-to-AM-conversion block.

B. Results

B.1 Verification results

The results are shown in Fig. 10. The implementation of the FM-to-AM-conversion algorithm has at $BER = 0.001$ about the same performance compared with the optimum non-coherent MSK receiver with hard decision each symbol time [13]. The delay τ is, in this experiment, 1 μs, which equals the symbol time. So the current symbol is multiplied with the previous one. This large delay causes no degradation in performance as can be seen in Fig. 10.

For a GMSK signal in our simulation model, the performance at $BER = 0.001$ has degraded about 3 dB, compared with the MSK signal. It is assumed that the Gaussian filter has a negative effect on the performance of the demodulator. The Gaussian filter lowers the output value for example of the '1' in the '010'-sequence (see Fig. 2). Furthermore, during the '1' period, a part of this cycle is negative, which has negative influence on the performance of the integrate-and-dump part.

For an FSK signal (with $h = 0.315$) the performance of our model has degraded about 10 dB compared with the optimum coherent FSK receiver (with $h = 0.3$) with hard decision each symbol time. We have not found a relation for a non-coherent FSK demodulator, but it is assumed that this demodulator has a worse performance compared with a coherent demodulator.

The huge difference between the theoretical line and the measured line is assumed to be caused by the fractional delay, needed by the FM-to-AM-conversion part. Whereas in the MSK and GMSK experiment a time delay of 1 μs was needed, in this experiment the time delay was set to 1.587 μs. This value can only be approximated by a maximal accuracy of $1/50 = 0.02$, due to a sample rate of 50 MHz. This estimation error causes a DC-offset in the output of the FM-to-AM-conversion block. Furthermore the delay has increased to about 1.5 symbol time. In this case the maximum frequency deviation (in the middle of the symbol time) is being multiplied with a transition between two symbols. It is assumed that the performance of the integrate-and-dump algorithm is heavily affected by these above mentioned effects.

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[2] The pre-detection filter which is located just before the FM-to-AM-converion block is not depicted in Fig. 9.

The performance of the demodulator for a measured Bluetooth GFSK signal has, compared with the measured FSK performance, degraded about 6 dB. The effect of the Gaussian filter on the performance of the demodulator when FSK is used, is larger than the difference in performance between MSK and GMSK. Bluetooth FSK signals have in comparison with MSK signals, less frequency deviation. The Gaussian filter will reduce this deviation even more. So it is assumed that the degradation caused by the Gaussian filter has more influence if the frequency deviation is lower.

B.2 In-band interference results

In order to determine the channel selection requirements for Bluetooth GFSK signals with $h = 0.315$, the influence of other Bluetooth signals in the wanted channel has been researched. In this experiment the SNR has been set, just below the required BER of 0.1%, to 30 dB. Furthermore a pre-detection filter has been used, which passes 99% of the wanted signal power.

In this experiment, our simulation model includes one Bluetooth interferer in the same channel as the wanted signal. The output signal strength of this interferer can be varied. The results are shown in Fig. 11. If the interferer has a signal strength of 0.005 (where 1 equals the signal strength of the wanted signal), the BER degradation can be neglected. (Note: The BER for SNR = 30 dB, without interferers, is about 0.0007.) So all in-band interferers have to be suppressed to $20log(0.005) = 22.4$ dB below the wanted signal strength.

V. Conclusions

In this paper we have analyzed one implementation of an FSK demodulation algorithm (based on the FM-to-AM-conversion method) for the use in Bluetooth systems. Furthermore we have analyzed the influence of in-band distortion. In-band interferers have to be suppressed to 22.4 dB below the signal strength of the wanted signal. It should be noted that this value is about 6 dB less than the required SNR for a BER of 0.1%. Further research should verify if other interferers should also be suppressed by this value.

The performance of the implementation of the FM-to-AM-conversion method is, compared with the optimum coherent FSK demodulator with $h = 0.3$, not so good. There are different explanations for this. First, our implementation uses a very simple phase-shift function, so the performance is expected to be worse compared with the optimum receiver. Furthermore there are several noise sources introduced by the implementation of the algorithm.

In our implementation, the time delay is equal to about 1.5 symbol time. In this case the maximum frequency deviation (in the middle of the symbol time) is being multiplied with a transition between two symbols. Furthermore, the delay can only be approximated by a maximal accuracy of 0.02. This estimation error causes a DC-offset in the output of the FM-to-AM-conversion block. It is assumed that the performance of the integrate-and-dump algorithm is affected by these effects mentioned above.

Moreover it is assumed that the Gaussian filter has a negative effect on the performance of the demodulator. The Gaussian filter lowers the output value of for example the '1' in the '010'-sequence. Furthermore, during the '1' period, a part of this cycle is negative, which has negative influence on the performance of the integrate-and-dump part.

For further research we investigate the following questions: What is the influence of the pre-detection filter? What are better phase-shift functions than the delay function? How do other GFSK demodulation algorithms perform? What is the (theoretically) optimal GFSK demodulator with $h = 0.315$? What is the performance gain, if demodulating algorithms are used, which use more than 1 symbol period for making a decision which symbol has been detected?

Acknowledgments

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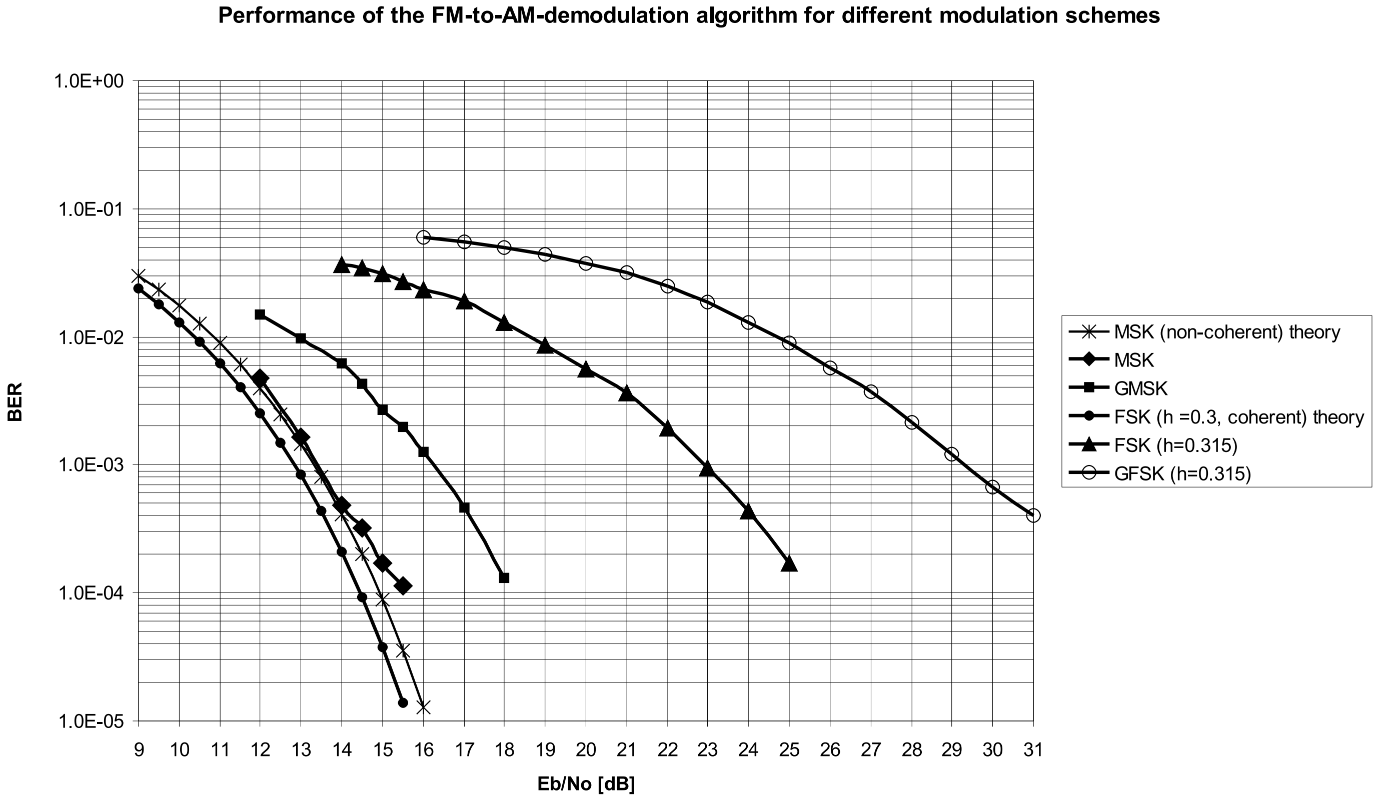

Fig. 10. BER versus SNR for different modulation schemes

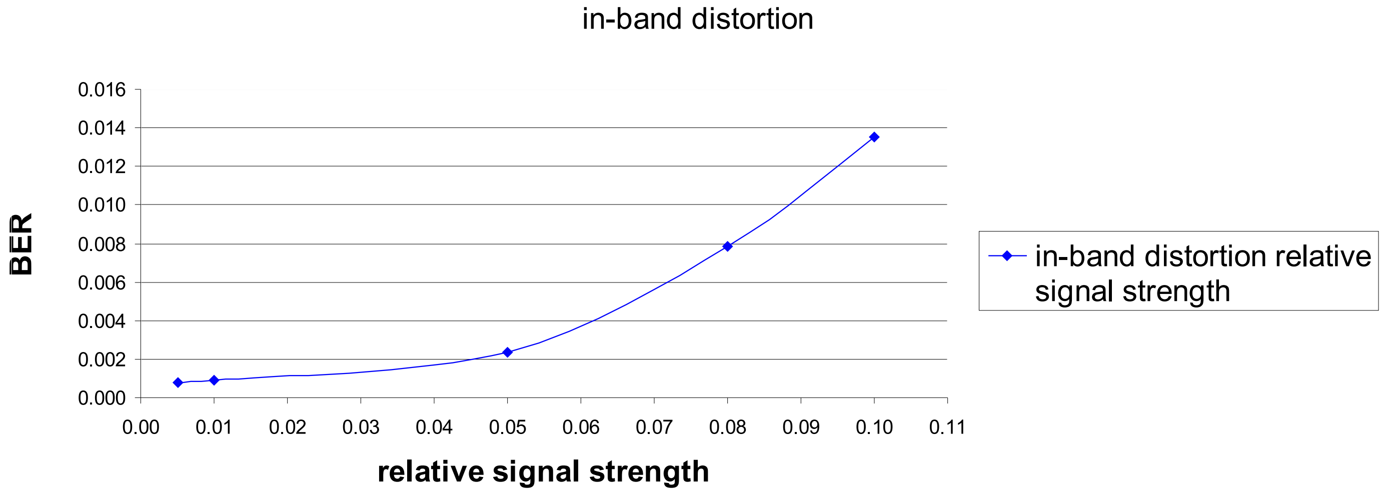

Fig. 11. BER versus signal strength of in-band interferer