Ultra Low Power UWB Modem Design: Experimental Verification and Performance Evaluation

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Abstract

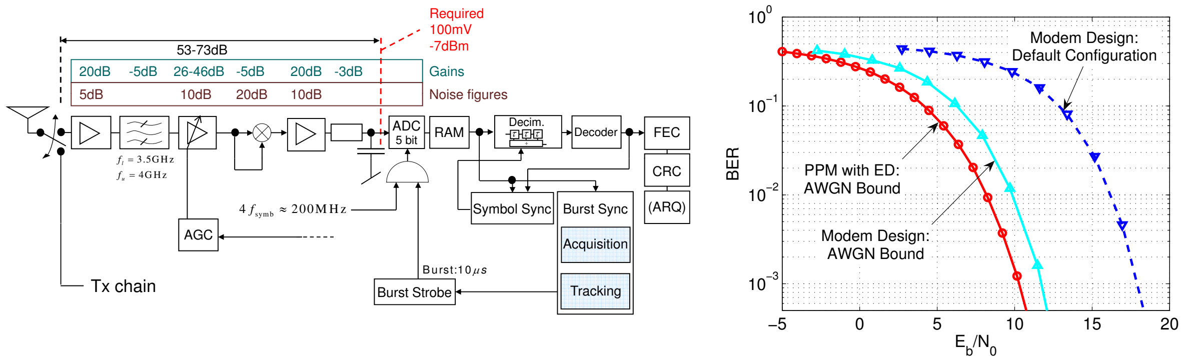
A major constraint in the design of wireless body area networks (BAN) and sensor networks is battery autonomy. For nodes with burst-wise transmission autonomy is efficiently achieved by sleep cycles. We have recently proposed an energy detection based ultra-wideband (UWB) transceiver structure featuring an average data rate of 500 kbps with a total power consumption of less than 1 mW. In this work we present an experimental testbed for our design, which is able to obtain over-the-air performance results and allows to directly observe the impact of physical effects of the environment on BAN communication. Based on the testbed we verify the functionality of our modem design in real world scenarios and evaluate its performance.

1. Introduction

Recently, ultra-wideband (UWB) wireless sensor and body area networks (BAN) gained much interest due to a multitude of attractive applications. In a BAN, several nodes are placed directly on the human body or very close to it. Since BAN nodes get their power from rechargeable batteries or by energy harvesting, it is inevitable that they are extremely energy efficient. A UWB system architecture for sensor networks has been presented in [1]. With 100% duty cycle operation a maximum data rate of 5 Mbps has been achieved requiring a current consumption of about 40 mA. In [2], a UWB demonstration system with coherent reception has been described where the front-end can be switched off during adjacent pulses. For the receiver part of this system a current consumption of about 16 mA has been estimated. Recently, we presented an energy detection based ultra-low power UWB system design with an overall estimated current consumption of about 0.45 mA [3]. Low duty cycle operation together with a high peak data rate are the key to achieve a medium data rate system with very low current consumption. Using binary pulse position modulation (PPM), data is transmitted at different time-shifts according to the different bit values. Having a delay spread of τ_{rms}=10 ns, the minimal PPM frame duration without inter-symbol interference (ISI) is restricted to 20 ns [4], implying a peak data rate of 50 Mbps. Requiring an average data rate of 500 kbps, a duty cycle of 1% can be realized. With respect to streaming applications, the maximum allowed latency time is set to 1 ms. Therefore, a burst of 500 bits and 10 μs duration is sent every millisecond. Besides the low duty cycle operation also the usage of low complexity resonant circuits in the analog part, which requires a moderate relative bandwidth, is important to achieve low power consumption. Hence, the frequency range from 3.5 to 4 GHz has been chosen for the design. The theoretical feasibility of the presented design respecting FCC power limits together with transmission of only one pulse per bit has been shown by means of computer simulation. In this paper we investigate the impact of physical effects such as interference from other wireless systems, different environments, antenna-body interaction and near field effects on the performance using an experimental testbed.

2. UWB Modem Design

An energy detector (ED) is used as receiver for the binary PPM. This type of receiver collects and compares the energy in both PPM half-frames to decode the data. A block diagram of the considered energy detection receiver chain, which shall be verified by the presented experimental testbed, is shown in Figure 1(a) together with noise figures and gains of the analog blocks. The receive signal is amplified by a low noise amplifier (LNA) and then filtered to reduce out-of-band interference. Subsequently, the signal is amplified by a variable gain amplifier (VGA), which is controlled by an automatic gain control (AGC), squared and amplified again. For complexity reasons, the subsequent integration is realized by a simple first order low-pass filter. The resulting analog signal is sampled by an analog-to-digital converter (ADC) with a free-running clock at four times the symbol rate, i.e, $f_{\mathrm{ADC}} = 200$ MHz. The random access memory (RAM) enables the storage of one whole burst. Thus, burst-wise processing is possible. After interpolation and down-sampling by the decimator, the decoder consists of a simple subtraction.



(a) Block diagram (b) AWGN performance

Figure 1: Modem design and performance of the UWB-ED receiver

In order to analyze the performance loss caused by our specific design, the bit error rate (BER) performance of the presented receiver structure is compared to the theoretical additive white Gaussian noise (AWGN) PPM performance bound for an ED in Figure 1(b). It can be seen that the performance of our design is about 1 dB worse, when all noise figures are set to 0. This is mainly due to non-ideal filters and integration. However, simulations with the default configuration, i.e, using noise figures and gains as specified in Figure 1(a), show a moderate signal-to-noise ratio (SNR) loss of about 5.4 dB.

3. Optimization of Receiver Parameters

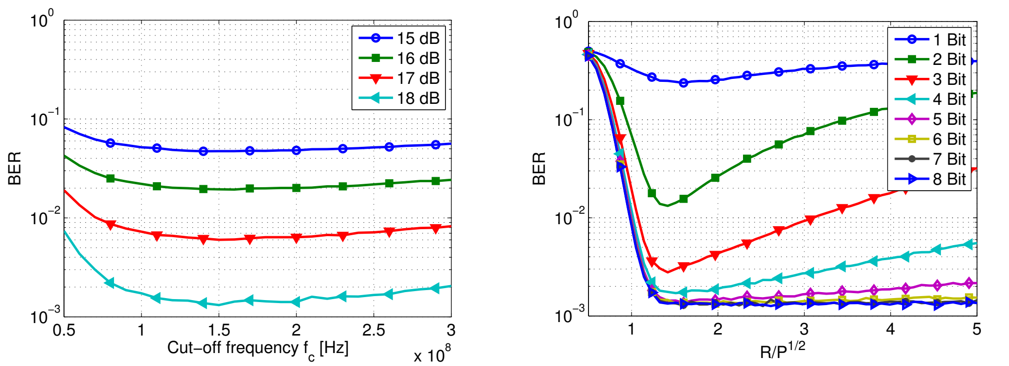
This section describes the parameter optimization of two main modem blocks of the presented design in Figure 1(a), i.e. the low-pass filter and analog-to-digital conversion. Performance evaluation is done by BER simulations for different design parameter using the impulse responses of ear-to-ear channels, measured in an anechoic chamber [5].

Low-pass filter: The integration operation is realized with a first order low-pass. Its transfer function is given by $H(f) = (1 + j2\pi\tau f)^{-1}$, which corresponds to an impulse response of $h(t) = 1/\tau \cdot \exp(-t/\tau)$ for $t > 0$. The cut-off frequency (bandwidth) is denoted as $f_c = (2\pi\tau)^{-1}$ and determines the integration time, where the ED collects the pulse energy. If the integration time is too short, not enough energy can be collected, whereas long integration times may increase the impact of noise and cause ISI by smearing the pulses too much [6]. The optimal filter bandwidth lies between the frame rate and the bandwidth of the pulse. However, the optimal filter bandwidth depends also on the time-dispersive UWB channel. An optimization with respect to the BER, using a set of 12 measured typical BAN channel impulse responses results in a cut-off frequency of $f_c = 150$ MHz. This value shows good performance for the desired application in body area networks. Figure 2(a) depicts exemplarily the simulated bit error performance versus the cut-off frequency for different SNRs for one measured channel realization.

ADC: Analog-to-digital conversion degrades the modem's performance due quantization noise and clipping [7]. The resolution of the ADC has a strong impact on the complexity and power consumption of the modem. The ADC complexity grows exponentially with the resolution and it heavily affects the complexity of the following digital signal processing, e.g. required memory size. Therefore a smart trade-off between complexity and performance loss due to quantization noise must be found. To simulate the impact of quantization noise and clipping, the input-output relation of the ADC has been modeled as

$$y_{\mathrm{adc}} = \begin{cases} 2^b - 1 & x_{\mathrm{adc}} > R \\ \left\lfloor x_{\mathrm{adc}} \cdot \frac{2^b-1}{R} + \Theta \right\rfloor \qquad \text{for} & 0 < x_{\mathrm{adc}} \leq R \\ 0 & x_{\mathrm{adc}} \leq 0 \end{cases} \tag{1}$$

where x_{adc}, y_{adc} are input and output signal, respectively. It is assumed that the power of the input signal P is hold constant by the AGC. R denotes the range of the ADC, i.e. the clipping limit, b the resolution and Θ is a random variable which is constant for one burst and uniformly distributed in $[0, 1]$. This additive offset models imperfections of AGC. Using this model the performance in terms of BER is simulated. The results are plotted in Figure 2(b) for a fixed SNR for one measured channel realization.



(a) Performance vs. low-pass cut-off frequency

(b) ADC range and resolution ($E_b/N_0 = 18$ dB)

Figure 2: Performance evaluation

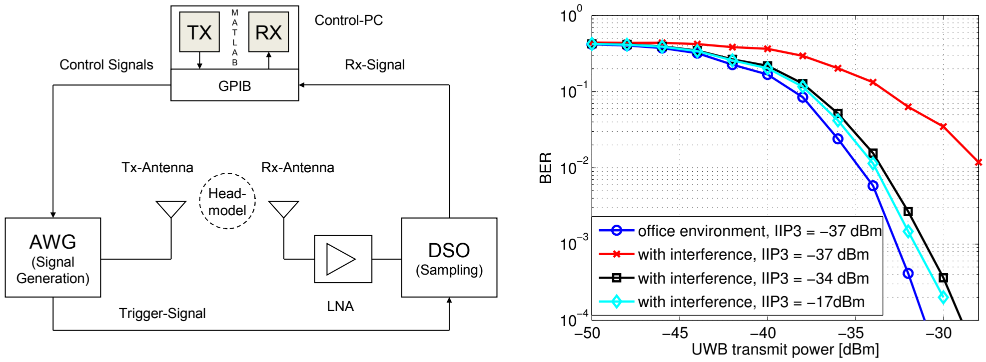
As results show, an ADC of 5 bits is sufficient for the proposed modem design. The performance does not increase significantly for higher resolutions. If the input range R of the ADC is chosen too small, the performance is degraded due to clipping. However, too large values of R lead to higher quantization noise, because only the less significant bits are utilized. The optimum operation point of the AGC can be read off in Figure 2(b). Note that this does not consider the possible influence of strong narrow band interference.

4. Over-the-air Performance Evaluation

For the performance evaluation a testbed (cf. 3(a)) consisting of a personal computer (PC), an arbitrary waveform generator (AWG - Tektronix AWG 7107), a digital sampling oscilloscope (DSO - Lecroy SDA 6000), two UWB antennas (Skycross SM3TO10MA), an external LNA, and a head model is set up. The trigger signal is used for burst synchronization, such that the DSO roughly knows the burst position. The external LNA with a gain of 42 dB, IIP3 of -22 dBm, and a noise figure of 1.4 dB is used to be able to disregard the high noise figure ($\approx$ 23 dB) of the DSO. In order to cancel the amplification of the LNA, the signal after the DSO is attenuated by 42 dB. The whole chain implies a cascaded noise figure of $\approx$ 5.8 dB compared to $\approx$ 5.4 dB of the original receiver chain described in Figure 1(a). The PC runs a graphical user interface (GUI), which allows to transmit data from the AWG to the DSO. The GUI supports a lot of analysis features, e.g. signal inspection in time and frequency domain after each building block of the receiver. Since the transmitter and receiver chains are implemented in software in a modular way, this testbed allows to test and evaluate basically any modulation format, transmit pulse shape, receiver structure, and synchronization algorithm, while still capturing the influence of the physical wireless channel, surrounding interfering wireless sources, and antenna-body interaction.

In the following, the over-the-air performance of our modem design with the in the previous section optimized parameters is investigated in an office environment for two different interference scenarios. In *scenario one* only interference from existing wireless systems such as GSM and UMTS base stations is present. For *scenario two* a controlled interference source is added at one meter distance to the UWB receive antenna. The source emits a continuous wave at 2.4 GHz with power 0 dBm, which corresponds to a power of about -50 dBm at the UWB receive antenna. The transmit power of the UWB device is varied from -50 dBm to -28 dBm, which is within the average and peak power limits issued by the FCC.

Figure 3(b) shows the obtained BERs for both scenarios and different IIP3 values of the LNA in Figure 1(a). The curve marked with '$\circ$' depicts the performance for *scenario one*. A transmit power of -33 dBm is required to achieve a BER of 10^{-3}. All other curves illustrate the performance for *scenario two*.



(a) Testbed setup

(b) BER performance for *scenario one* and *two*

Figure 3: Experimental testbed and measurement results

It can be seen that the nonlinearity of the LNA degrades the performance significantly, if a strong interferer is present. An IIP3 of -37 dBm implies that the 1 dB compression point is in the order of magnitude of the interference power, which explains the significant performance degradation. However, increasing the IIP3 to -34 dBm gives an acceptable SNR loss of about 2 dB at a BER of 10^{-3}.

5. Conclusions

A testbed for our modem design based on an AWG as transmitter and a DSO as receiver is presented. Using experimental performance evaluation, reliable BAN communication at a peak data rate of 50 Mbps is shown in an office environment, while respecting FCC limits. The influence of a narrowband interference is investigated and linearity requirements for the LNA are discussed.

References

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