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BPSK & QPSK Modulated Data Communication for Biomedical Monitoring Sensor Network

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Abstract— **Data communication between body-mounted sensors is progressing towards wireless monitoring networks. In this work, digital data communication by galvanic coupling through the body is presented as a promising approach for wireless intra-body communication. The human body itself serves as the transmission medium of electrical current. Both binary and quadrature phase-shift-keying (BPSK and QPSK) modulated data transmissions are implemented and compared for galvanic coupled links between 2 differential electrode pairs. The adaptive system offers up to 1 mA maximum current amplitude between 10 kHz and 1 MHz. Data communication at a rate of up to 64 kbit/s was realized with BER of 10^{-4} corresponding to an SNR greater than 6 dB. The novel technology has shown its feasibility in clinical trials. Furthermore, such a low-current approach enables data communication that is more energy-saving than other wireless technologies.**

I. INTRODUCTION

Medicine and health care could greatly benefit from data communication between body-mounted sensors for patient monitoring applications. Especially for long-term risk patients, this new wireless technology offers substantially increased freedom during ECG, pulsoximetry or body temperature surveillance. Such data links require a rather low but reliable data rate. Several networks have been designed for application in personal electronic devices like Palm Pilots and mobile phones with data rates of 100 kbit/s and more. Power consumption could be lowered by more than an order of magnitude for extremely short-range systems (less than 2 m). However, none of these networks has been optimized for medical devices, which is necessary to meet the demands of mobile patient monitoring systems. The technology and networking concept for intra-body communication are driven by the conviction that only a novel approach can meet the needs of personal medical assistants. Biomedical signals like electrocardiograms are recorded and transmitted without any additional wires through the human body to a receiver device (Fig. 1). The human body itself acts as the conducting medium to transmit a low data rate signal through electrical coupling.

Various electrical coupling methods have shown the potential of data communication through the human body [1], [2]. The method of galvanic coupling was investigated by Oberle [3] and analyzed by Hachisuka *et al.* [4]. The characterization of the human body as data link between body parts is shown in [5]. An attenuation of up to 60 dB was found for the transmission channel human body. Based on these results, a transceiver with direct-coupled interface was presented as a low-power approach with high data rate [6].

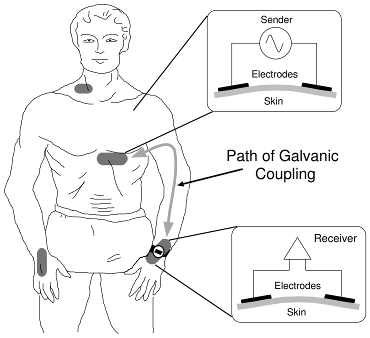

Fig. 1. Intra-body data communication between body-mounted sensors

In this paper, galvanic coupling is introduced as a promising approach for wireless intra-body communication. A binary or quadrature phase-shift-keying (BPSK and QPSK) modulated data stream is transmitted by coupling alternating current through a pair of differential electrodes. The receiver unit provides analog filtering in the desired frequency window and gain of up to 72 dB. Digital signal processing includes automatic gain control, carrier and symbol synchronization and framing. A data communication rate of up to 64 kbit/s was realized with a BER of 10^{-4} at an SNR of greater than 6 dB.

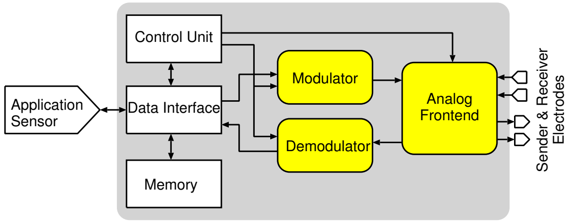

Fig. 2. Simplified block diagram of the intra-body communication transceiver for modulation and demodulation of sensor data and transmission using differential electrode pairs

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II. TRANSCEIVER ARCHITECTURE

A. System Overview and Specifications

Figure 2 shows a simplified block diagram of an intra-body communication device. It contains a data interface unit which samples, processes and digitizes the analog signals from the biomedical sensors. Digital baseband processing conducts encoding, modulation and demodulation. The sensor data is transmitted to a link sensor (Fig. 3), which collects and forwards the received data from all applied sensors to further monitoring devices.

Body sensor applications are driven by the need for power efficiency. The power efficiency describes the ability of a modulation technique to preserve the fidelity of the digital message at low power levels. It is represented by the ratio of signal energy per bit to noise power spectral density (E_b/N_0) required at the receiver input for a certain error probability. Knowledge about signal strengths are a must to design optimal devices. The power consumed by such devices can be divided into three major categories:

- sensor signal conditioning and storage
- baseband signal processing
- analog front-end for wireless communication

Using the human body to transmit data requires operation at frequencies between 10 kHz and 1 MHz, making intra-body communication devices inherently more efficient than higher frequency radio transmitters. The decision not to transmit at frequencies less than 10 kHz is based on the common understanding that biomedical signals exist up to this frequency. Transmission within this band might therefore have impact on biomedical functions of the patient and therefore requires additional consideration. Since intra-body communication represents a novel technology, type approval is mainly concerned with the limits of contact currents. Existing regulations and recommendations for exposure limitations for intra-body communication are based on studies and recommendations of the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [7].

B. Applications

The existing potential of intra-body communication can be determined by identifying sensors which are physically small and which are essential enough to cover the required technical effort (Table I). The sensors are not implanted but remain extra-corporal; the expected data rate is low and the percentage of sales and application in ambulatory medicine or home care is high enough to be of relevance. Hospitals seem to prefer a combination, e.g., electrocardiograpgy and pulse-oximetry (ECG-SpO_2). Data rates up to 10 kbps for the raw sensor data are required. This does not include the possibility of reducing the data to be transmitted through sophisticated data compression algorithms.

TABLE I

BIOMEDICAL SENSOR APPLICATIONS [8]

Parameter	Sampling Frequency [HZ]	Data rate with 12-bit
Blood pressure	60	1.44 kbit/s
ECG 1-point	250	6 kbit/s
ECG 12-point	250	72 kbit/s
Body temperature	0.1	2.4 bit/s
Pulse oximetry (SpO2)	300	7.2 kbit/s

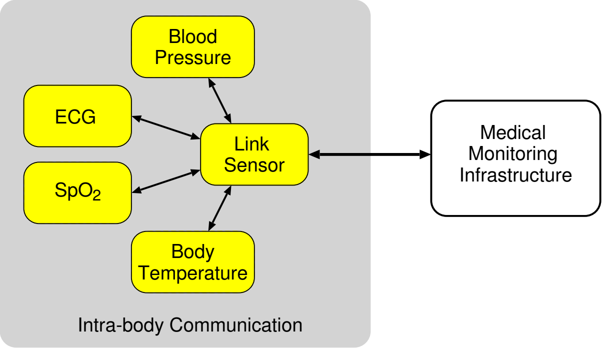

Fig. 3. Simplified overview of the intra-body communication network: bi-directional data communication between sensor units and central link sensor as well as external link to further monitoring infrastructure

C. Network Architecture

Figure 3 shows the structure of the intra-body network, which can operate independently, similar to an intranet and without any link to external devices. Communication is bi-directional, and the network is based on a point-to-multipoint architecture. The link sensor serves as a base station for the different sensor devices, such as ECG or SpO_2 sensors. Wireless or wireline point-to-point communication connects the network to external devices like notebooks, databases or mobiles.

This work is primarily concerned with the first OSI layer, the physical layer, examining the electrical properties of the communication channel, and the second layer, establishing a reliable information link, in order to implement a working prototype of tissue-coupled devices. The ISO network standard allows incorporation of intra-body communication devices into an application, by developing a third layer to connect the intra-body communication devices with each other.

A communication network is primarily judged by channel capacity, with a theoretical limit defined by the Hartley-Shannon law

$$C = BW \times log_2(1 + \frac{S}{N}) \qquad (1)$$

where C is the channel capacity in bps, BW is bandwidth, and $\frac{S}{N}$ is the signal-to-noise ratio (SNR). To achieve a high channel capacity for a fixed bandwidth, the SNR must be maximized. This depends on the transmitter signal strength, the channel as well as the receiver sensitivity and noise performance.

Assuming a channel bandwidth of 128 kHz and a modest but realistic SNR of 10, the maximum channel capacity will be 442 kbps. The overhead due to synchronization and TDMA communication will cover up to 30 percent of the available data rate.

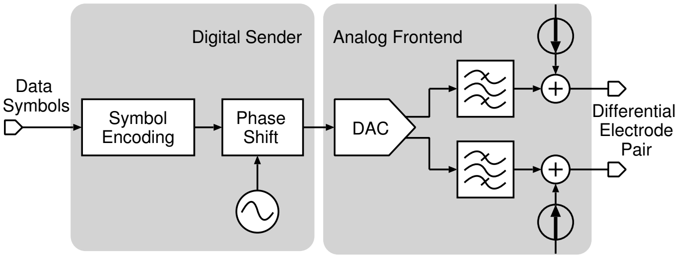

Fig. 4. Simplified block diagram of the sender with digital unit (including symbol encoding and phase shift modulation) and analog front-end (providing DA-convertion, filtering and current output stage)

D. Modulation

With narrow-band transmission, the carrier can be digitally modulated by switching the signal (on-off keying; OOK), frequency (frequency shift keying; FSK) or phase of the carrier (phase shift keying; PSK). The bandwidth of all three techniques is approximately equal to the signaling rate. Phase shift keying is a widely used modulation format for low bit-rate applications and moderate error performance. Therefore, BPSK and the more complex form QPSK seem to be suitable due to simplicity and hardware cost.

Typically, PSK detection consists of two matched bandpass filters tuned to the carrier frequency and the phase shift, respectively, plus a symbol detector and decision circuit. Coherent PSK detection uses synchronous detection for better noise rejection performance but needs to synchronize to the frequency of the sender. An optimal solution focuses on low power consumption and reduced complexity at reasonable data rates.

For low-power operation it is important to know the minimum required output power of the transmitter to guarantee signal detection at the receiver input. The output power requirement of the transmitter is therefore determined by:

- noise from the electronic system
- noise from the interfacing electrodes
- the chosen modulation scheme
- the channel attenuation
- the type approval requirements

Noise contribution from the receiver input itself is best described by the input noise figure of the receiver front-end, or $N = 4kTR_{input}$. Since receiver front-end is characterized by high-gain and low-noise amplifiers, it can be assumed that mainly the front-end of the receiver contributes to the equivalent input noise of the circuitry. The electrode-skin contact resistance is about 1 kΩ for pre-gelled electrodes, and the required SNR at the receiver input for reliable detection is at least 8 dB. This gives a minimum transmitter output power of -14 dBm for 2.5 kΩ electrode/tissue load and 3 V supply, compensating a channel attenuation of at least 45 dB. The maximum output power is limited by the ICNRP guidelines to 8 dBm.

III. DESIGN OF THE DEMONSTRATOR

A. Hardware Design

The design of the demonstrator is a trade-off between complexity, bandwidth efficiency and power consumption. Since most of the building blocks should ultimately be integrated onto a single chip, the system design is challenged by:

- low power consumption to maintain at least 24 hours of reliable operation
- detection of μV signals at the input of the data acquisition unit and at the receiver

The following subsections describe the main building blocks of the demonstrator and illustrate the demonstrator setup of an unidirectional link between sender and receiver units.

B. Sender Unit

Figure 4 shows a block diagram of the sender. Data symbols containing sensor information are combined into a transmission frame of 1024 data bytes plus two words for synchronization (see Fig. 5). With this simple communication protocol it is possible to perform unidirectional digital communication between a sensor unit and the link sensor.

The digital sensor data modulate the output signal of the sine wave generator by switching the phase counter. Shifting between the clock phases modulates the output signal as BPSK or QPSK depending on the symbol encoding.

The signals generated in the digital sender unit are fed through a 12-bit digital-to-analog converter into a differential current output stage capable of a maximum amplitude of 1 mA. The coupling of the signal currents into the human tissue is performed through two electrodes attached to the skin.

C. Receiver Unit

Figure 6 shows a simplified block diagram of the receiver unit.

A passive RC network at the front-end of the receiver suppresses out-of-band noise as well as DC offset, which is due to the expected drift of the electrode-skin contact. The gain of 20 dB for the differential instrumentation amplifier is sufficiently high with respect to the noise figure of the filter stages. A programmable gain amplifier with amplification up to 72 dB controlled by the digital receiver finalizes the analog signal processing. The signal is sampled by a 14-bit analog-to-digital converter at a sampling rate of 8 MSPS.

Figure 7 shows a simplified block diagram of the demodulator. The amplified and digitized receiver signal is demodulated

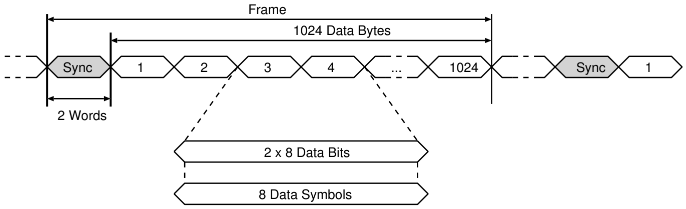

Fig. 5. Communication protocol for unidirectional communication between the sensor device and receiving link sensor

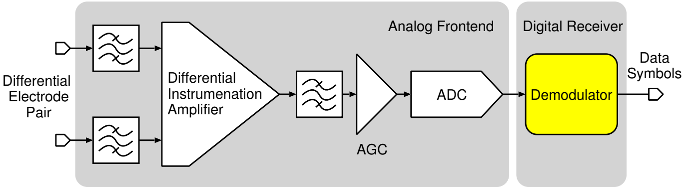

Fig. 6. Simplified block diagram of the receiver with analog front-end (amplifier, band filter, automatic gain-control and ADC) and digital receiver

and the symbols are detected. While the hardware complexity for carrier synchronization and filtering is almost the same for QPSK and BPSK, the hardware complexity of symbol synchronization in QPSK is a factor of 2. Nevertheless the bit rate is doubled for QPSK.

D. Demonstrator Assembly and Integration Complexity

The entire transmitter unit, including a sender and a receiver unit for bidirectional communication, has the size of a credit card. The digital unit with data interface, modulator and demodulator units uses 1200 slice units of the XILINX SPARTAN IIE FPGA for BPSK and around 10% more for QPSK. The analog part is built with discrete elements. The sensor unit is battery powered with 3 V. In order to identify possible impacts from the electrode size and contacts, various commonly used electrode types were tested; *Blue Sensor BR* was selected. The key design parameters are listed in Table II. An ASIC integration of the digital sender and receiver units in a 0.25 μm process will occupy an area of 1.1 mm^2.

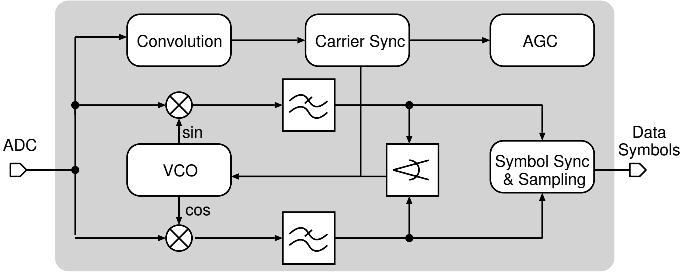

Fig. 7. Simplified bock diagram of the demodulator including down conversion, phase estimation, carrier and symbol synchronization as well as sampling detection units

TABLE II

KEY PARAMETERS

Parameter	Value
Supply	3 V
Frequency range	10 kHz - 1 MHz
Maximum amplitude	1 mA
Maximal attenuation	72 dB
Convert (DA, AD)	12-bit, 14-bit
Sampling rate	8 MSPS
Maximal data rate	255 kbit/s
Modulation	BPSK, QPSK
Blue sensor BR electrodes	560 mm^2 solid-gel

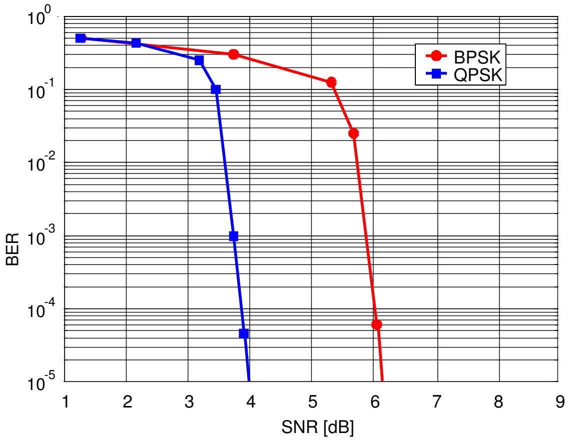

Fig. 8. Bit error rate (BER) in relation to the signal to noise ratio (SNR) comparing BPSK and QPSK modulation scheme with a carrier frequency of 256 kHz and a data rate of 64 kbit/s

IV. CONCLUSION

Galvanic coupling is a promising approach for intra-body communication. The versatile prototype presented allows the investigation of dedicated signal frequencies and modulation types. Digital data can be transmitted through the human body at reasonable rates of several 10 kbps. Data transfer up to 64 kbit/s has been achieved with BPSK and QPSK digital modulation types and BER of 10^{-4} corresponding to an SNR greater than 6 dB (Fig. 8). Tests have proven the feasibility of the concept for single-channel data transmission at frequencies less than a few hundred kHz. The presented solution is very attractive for biomedical applications with long-term monitoring of patients, where power is tight and miniaturization a must.

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