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In-vivo signal transmission using an intra-corporal RF transmitter

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***Abstract*—In clinical routine, measurements of human physiological parameters are very important. In this paper, a study of RF transmission from the inside to the outside of a biological body is described. In the course of this work, an overview of the state of the art of wireless biotelemetry and the basics of biological tissue attenuation are given. In addition, several prototype transmitters were designed and developed with frequencies ranging from 50 to 700 MHz. With these transmitters a study of an in-vivo transmission was run to measure realistic attenuation values of a living biological subject. In the evaluation phase, a prototype transmitter was placed in the esophagus, near the heart, of a narcotized living pig. This allows demonstrating the transmission out of an animal with human-like tissue properties. The results show a possible transmission at 58, 119, 240, 418 and 672 MHz with acceptable loss.**

I. INTRODUCTION

Wirelessly communicating implants are becoming more and more important for clinical research. With an implantable radiofrequency transmitter it would be possible to measure, record and transmit vital parameters without percutaneous wires. Biotelemetry sensors reduce infection risks, because they transmit information in-vivo via radio waves. A miniaturized biotelemetry transmitter allows for periodical measurements inside the human body.

Up to now, most parameters of human physiology are measured and analyzed non-periodically. In case of medical suspicion, additional measurements must be performed in order to achieve a well-founded diagnosis. However, existing measurements are problematic. For example, if measured in discontinuous time periods, the values show a high intra-individual variability of up to 33 % (e.g. intraocular pressure) [1]. Moreover, some parameters differ over the day. In order to obtain reliable results, measurements need to be repeated in short periods, e.g. shorter than one hour. This allows for detecting vital values that are too low or too high.

Usually, non-invasive blood pressure measurements are being performed using a pressure sleeve. The upper tissue is being compressed by the sleeve. In order to measure the blood's glucose level, it is necessary to injure the skin. Oftentimes, hospitalized or home care patients need to measure the parameters themselves. This represents a big source of error, as they often misuse the measurement device.

These examples show that there is a tremendous need for systems that allow for measuring continuously. These systems should receive and analyze data in distinct periods, thus eliminating the risk of errors caused by manual measurements.

II. WIRELESS BIOTELEMETRY: STATE OF THE ART

Wirelessly communicating implants are of high interest to many physicians. These systems send vital parameters to an extra-corporal receiver for further recordings and analyses. These parameters can include blood pressure, temperature, intra-ocular pressure, blood glucose values and others. The following paragraphs provide an overview over already existing systems that transmit data acquired intra-corporally to an extra-corporal receiver.

A. Wireless Capsule Endoscope ("Pillcam")

For examinations of the gastrointestinal tract, a little capsule can be taken orally. It is moving naturally through the alimentary tract. The "Pillcam" includes a telemetry part, a CCD camera and a power supply for illumination. A body waistcoat detects the position of the capsule and activates it. It also works as a passive power supply for the picture transmissions. [2], [3]

B. Wireless blood pressure and blood flow measurement systems

Existing implantable devices for measuring the arterial blood pressure and blood flow are always powered by external inductive sources [4], [5]. Advanced devices already have their own energy source; they have the size of a pacemaker, and can measure the parameters atrioventricular by a catheter. Such an implant has integrated circuits for the processing and remote transmission of measurements. Through an extra-corporal programming unit, these values are recorded. If necessary, the programming unit adjust the parameters of the intra-corporal electronics [6]. Promising analyses at Perdue University, West Lafayette (USA), are dealing with the use of arterial or venous stents as dipole antennas, which could allow patients a more natural mobility. As the signal can be transmitted over a distance of

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one to two meters, the patient does not need to wear the recipient on his body [7].

C. *Stress measurement on orthopedic implants*

For an optimal biomechanical design, long-term tolerability and rehabilitation load measurements are carried out on implants. Different than mathematical models, the measured results reflect the real values. These implants are used in shoulder or hip prostheses. An external receiver or computer is measuring pressure, temperature and the occurring moments that are transmitted via radio frequency pulses. Power is supplied by an external source inductively. [8]

D. *Additional opportunities for biotelemetry*

It is possible to develop further implantable sensors that measure the vital signs directly, and at the same time occupy little space, so that they can be implanted by minimal invasive surgery. The quantities to be measured include blood pressure, blood flow, hemoglobin levels, cerebrospinal fluid pressure, intraocular pressure, joint pressure and temperature.

III. SIGNAL TRANSMISSION THROUGH BIOLOGICAL TISSUE

A. *Attenuation of tissue measured by different methods*

As a first step, it is necessary to find the frequency band with the most suitable communication channel for a RF data transmission from inside the human body to an external receiver.

With formulas, the dielectric loss and the dielectric attenuation can be calculated [9]. [10] and [11] are displaying a linearity rise of the dielectric attenuation over the frequency range from 50 MHz to 1 GHz.

B. *Concept of an intra-corporal transmitter*

In order to send intra-corporal information to an extra-corporal receiver the signal has to pass several layers of human tissue. The flow chart in Fig. 2 shows a possible biotelemetry system for intra-corporal use. In addition, the transmitter has to work in a very limited space with ultra-low power, because implantable sensors are small. For implementing the signal transmission of intra-corporal sensors, the frequency modulation technique is preferred. This technique has a reduced circuit complexity as compared to the digital transmission protocols. Under these conditions, an analog and low-power system is obligatory. MAXIM-Dallas is producing several integrated circuits (IC). They are working at a frequency range between 50 MHz and up to 650 MHz (in the experiment at hand even up to 700 MHz caused by the used electronic components) with an included voltage controlled oscillator (VCO) that moves the intermediate frequency.

C. *Animal experiment*

The attenuation characteristics of the intra-corporal transmitter were tested with materials comparable to biological tissue [10]. The aim of the experiment was to obtain realistic properties for wireless biotelemetry.

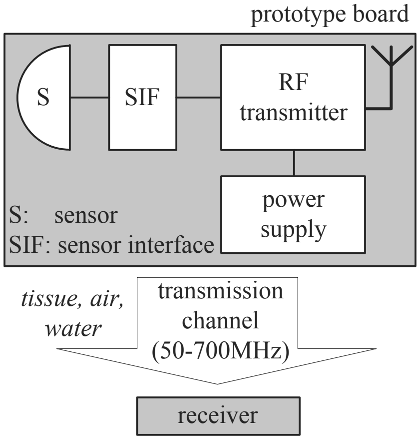


Fig. 1 Block diagram of the RF transmitter board.
The sensor gets relevant information which is changed by the sensor interface. The RF transmitter produces an analog frequency modulated signal. This signal should be sent through tissue, air or water to a receiver. The working frequency bandwidth is between 50 MHz and 700 MHz.

After the approval of the responsible ethics commission, three pigs were used as test subjects for this study.

We tested the transmitters, which were embedded in biocompatible capsules, with these pigs. The animals have biological characteristics comparable to those of the human organism and animals of the mammalian class. An overview of biological tissue properties is shown in [10], [11].

In order to get realistic transmission properties it is necessary to send low-power signals in-vivo of a biological, living subject. In the experiment, three pigs with the same age, gender and weight were used. The pigs were healthy and narcotized. In a first step, the encapsulated transmitter was placed in the esophagus, close to the heart.

The frequency range was determined by the components that were used to build the transmitter circuits. For the experiment the following frequencies could be generated: 58 MHz, 119 MHz, 240 MHz, 418 MHz, and 672 MHz.

IV. RESULTS

A. *Encapsulated transmitter circuit*

In order to reduce power consumption, the miniaturized transmitter was modified. This prototype (Fig. 2) has a size of 13 x 33 mm and can be used for experimental animal tests. Power for the transmitter is provided by two 1.5 V button cells. Furthermore, a biocompatible capsule made of ABS plastic has been produced by rapid prototyping

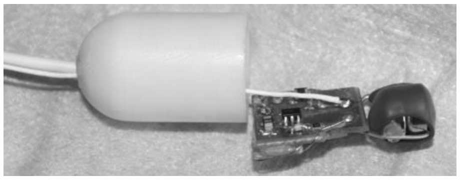


Fig. 2 Capsule and the transmitter PCB.
The capsule has a diameter of 13 and a length of 33 mm. It contains the transmitter, the antenna, and two button cells each with 1.5 V.

methods for complex three-dimensional shapes.

B. Attenuation of the in-vivo transmission

Five transmitters were used for the animal experiments. Each transmitter has one of the above-mentioned frequencies. One-by-one, the transmitters were put inside the capsules, which were then being placed near the heart.

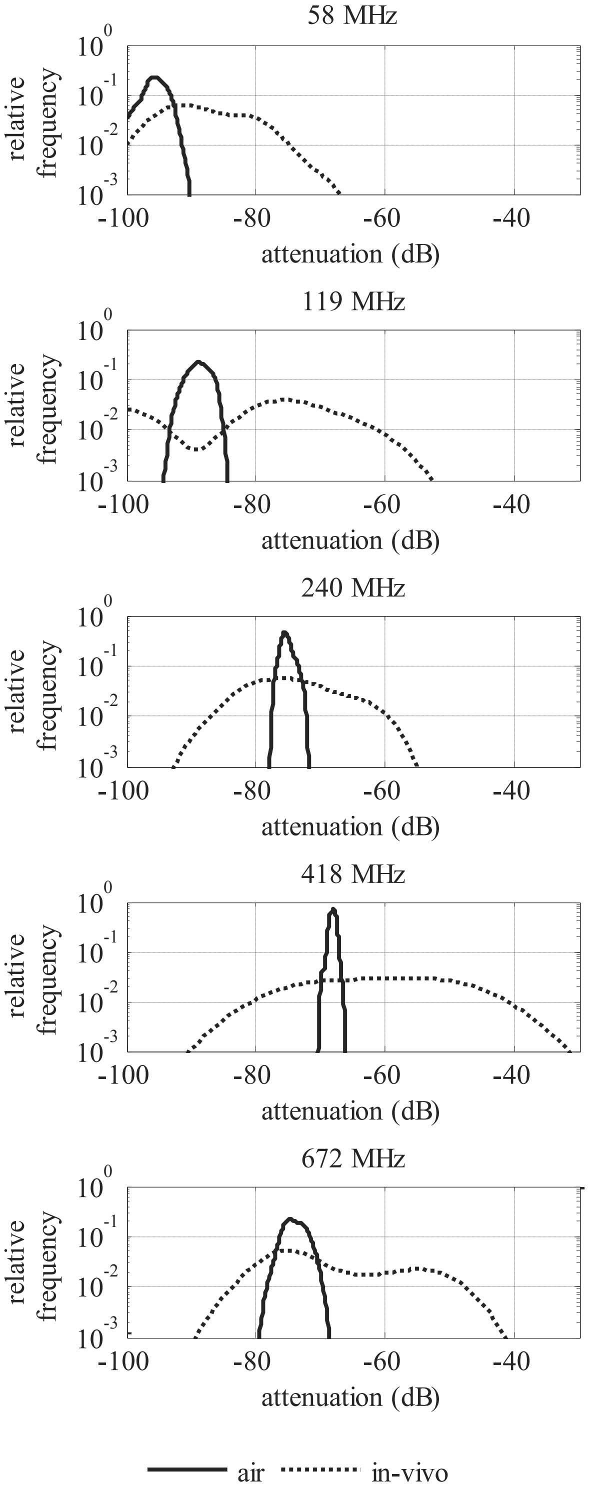
Fig. 3 shows the capsule position using an X-ray photograph. Fig. 4 shows the relative frequency of the transmitters' signal strength. First, the signal strength was measured in free air at a distance of 2 m (Fig. 4, solid line) over a period of 30 s. Then, a second measurement recorded the in-vivo signal from inside the pig to the outside (Fig. 4, dashed line) for another 30 s. The distance was 2 m as well. Comparing the transmission in free air to in-vivo, the attenuation increases in nearly all cases (Fig. 4). The transmission power was between 100 nW at 58 MHz and 1000 nW at 672 MHz. With rising frequency up to 418 MHz, the attenuation decreases. The attenuation at 672 MHz is similar to that at 240 MHz. At the first four center frequencies the standard deviation increased when the transmission was in-vivo (Table I). The best results, in free air as well as in-vivo, were achieved at a transmission frequency of 418 MHz.

A high standard deviation means that the signal amplitude was fluctuating strongly. At 240 MHz the mean of free air transmission (-74.34 dB) and outside the pig (-75.21 dB) do not significantly change. The standard deviation ranges from 0.95 up to 6.56 dB.

V. DISCUSSION

Measurements of an in-vivo signal transmission show that the frequency significantly influences the transmission characteristics. Normally, the signal strength decreases as soon as the source is surrounded by lossy material. The signal quality increases with an increasing sending frequency in free air. But the dielectric attenuation of biological tissue and the transmission frequency have a linear dependency [10]. So, the tissue should attenuate the signal stronger at a high frequency. The transmitters used in the experiment have a transmission power with a nearly linear dependency to the frequency. The transmitter with 58 MHz has a lower sending power compared to the 672 MHz transmitter. Despite higher transmission power the receiving power decreases. Previous tests with water

Fig. 3 Animal experiment.
The transmitter was placed near the heart (circle). The transmitter and the power supply were put into the capsule. To get the real position in the esophagus, an X-ray photograph was taken. This picture is a photo montage of the X-ray and the real photograph.



58 MHz

119 MHz

240 MHz

418 MHz

672 MHz

Fig. 4 Relative frequency of the attenuation
A wide and flat plot describes bad signal detection; a peak describes good detection. In the first case it was undamped by the air. The tissue of the pig has dielectric lossy characteristics. The in-vivo signal was highly damped, readily identifiable by low relative frequencies (dotted line). The signal could be detected with a bad signal to noise ratio (SNR).

TABLE I
MEAN AND STANDARD DEVIATION OF ATTENUATION

f (MHz)	mean (dB), air	mean (dB), pig	std. deviation (dB), air	std. deviation (dB), pig
58	-95.73	-87.88	1.79	6.15
119	-88.86	-82.50	1.62	13.71
240	-75.21	-74.34	0.95	6.56
418	-68.14	-60.68	0.53	9.81
672	-73.98	-67.99	1.58	9.95

phantoms have shown that the transmission power enhances with the rising sending frequency and have thus confirmed this effect. The attenuation was even higher in a NaCl-solution with conductivity like blood [10].

For the five sending frequencies the best signal-to-noise-ratio was recognizable at 418 MHz (Fig. 4). The fact that the attenuation is not as high as expected at high frequencies can be caused by biological characteristics of the organism, maladjusted antennas, and a higher transmission power at higher frequencies. Another possible assertion is that the organism builds a kind of antenna with its whole body. This way, the signal could be transmitted over the tissue and the skin as a virtual antenna and could be sent to the extra-corporal receiver. The living tissue conducts the signal instead of intensely attenuating it, because human or animal body fluids (blood, cell liquid) are strong electrolytes. These electrolytes have a high electric conductivity [12]. However there is also a significant portion of dielectric loss (theoretically calculated [9]). Hands, the experiments conducted in this study disagree with the theory. The reason for the high standard derivation could be caused by the living biological subject. The respiration or the muscles generate artifacts that influence the signal transmission over the time of measurement.

The same holds true for radio waves: with bad radio reception, a contact with the antenna is enough to improve it. Similar effects were assessed in previous experiments, like the water phantoms, that were conducted in preparation of the animal tests. The signal strength rose when the transmitter was inside the water phantom or touched by a test person. At 418 MHz there was a possible resonance of the organs, body liquids, body dimensions, and the antenna.

VI. CONCLUSION AND OUTLOOK

By using RF transmitters from 50 MHz up to 700 MHz, an in-vivo signal transmission and reception was possible. For the experiment, three narcotized pigs were used. The frequency modulation was generated by several ICs from MAXIM. Therefore, it was possible to design compact transmitter boards.

The best results were obtained at 418 MHz. This is why, we can say that the attenuation values are not only a function of frequency, but also of the tissue's water or electrolyte content. Based on theoretical considerations, the lowest transmission frequency should yield the best results. In the animal experiment, however, it turned out that the lowest loss was established at a high frequency (here: 418 MHz), as compared to the other frequency ranges. The experiments document a low-power in-vivo transmission with successful signal transmission and detection. For subsequent studies another transmitter should be used which is able to switch the transmission frequency over a wide range from 50 MHz up to 700 MHz or even more.

In the next steps, the transmitter should be reduced in size. Doing this, the power consumption should be reduced too. A smaller capsule containing the transmitter could be transplanted subcutaneously.

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