Benefits and Limits of UWB for In- and Out-of-Body Communication

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Abstract

This work investigates the characteristics of the wireless in-body communication channel within the UWB frequency range from 3 GHz to 6 GHz. A series of experiments using a liquid human phantom is carried out in order to determine optimal transmission parameters for compact, high performance ingestible and implantable wireless medical devices. Although suited for low power and high throughput applications, UWB is strongly limited by the high attenuation in tissues in the microwave frequency range. Transmission loss measurements performed with an 11 mm loop antenna and an UWB transceiver prototype confirm this assumption. We therefore suggest using moderately wideband modulation techniques at the lowest frequency end of the UWB range.

1. Introduction

Thanks to their flexibility and versatility, wireless technologies find an ever increasing number of applications also in the medical domain. The ongoing trend towards miniaturization of electronic devices enabled diagnosis methods that were unthinkable several years ago.

As an example, the availability of small, low power wireless devices extended their field of application to implants and wireless in-body imaging. The use of miniaturized wireless cameras has been very successful in the field of gastroenterology, where the use of wireless capsule endoscopes (WCE) enables a painless visual examination of the entire digestive tract, a thing that cannot be achieved using traditional endoscopy tools.

These advantages do not come without compromises, however. Image quality wise there is still a considerable gap between a capsule and a conventional wired endoscope. The precision of the diagnosis is limited and has not yet reached its optimum. Thanks to the advances in integrated circuit technology, the amount of data that can be recorded and processed within the restricted power envelope of an ingestible capsule endoscope is constantly increasing. The image resolution and frame rate of commercial capsule endoscopes have improved with each generation, narrowing the gap to their wired counterparts.

In order to save CPU power and keep video latency low, the data transmitted by a WCE typically consists of a barely processed and hence essentially uncompressed video stream. Any improvement of the image definition calls for a corresponding capacity increase of the wireless link of the WCE. Its data rate must keep pace with the high quality content to be transmitted while preserving its very low power operation. Signal losses encountered in biological tissue get increasingly noticeable. Literature suggests several approaches how to face this challenge. UWB technology is a promising candidate for miniature high data rate applications because of its virtually unlimited available spectral bandwidth and a frequency range allowing for efficient small-sized antennas. An example of an UWB based prototype capsule endoscope operating at 10 Mbit/s is presented in [1]. The rather large implementation was successfully tested in a living pig.

A major limitation of the approaches using high carrier frequencies is the signal attenuation in biological tissue, known to be increasingly lossy towards microwave frequencies [2], reaching signal attenuations in the order of 10 dB/cm at 2.5 GHz [3]. At the same time, the limited energy source as well as the prevention of excessive local SAR values [4] limit the maximal transmission power to a few milliwatts. Therefore, keeping path losses as low as possible is essential for high data rates wireless in-body devices. FDTD simulations of the far field created by ingested sources showed the maximum radiation intensity to be expected between 450 and 900 MHz [5-7]. Other simulation studies [6] show a more differentiated picture and suggest to consider also frequencies between 1.2 GHz and 3 GHz for high data rate applications. Research studies providing experimental data on the in-body wireless channel are scarce, however. Experiments found in capsule endoscopy related literature mainly consist of system validations at a predetermined center frequency in a very specific setup. For a more thorough overview of the channel losses, systematic broadband measurements are therefore required. The goal of this work is to provide an experimental characterization on the wireless in-body channel in the UWB frequency range.

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2. Material and Methods

Two scenarios are investigated in this paper, in-body and out-of-body transmission. The In-body scenario assumes both the transmitter and the receiver to be located inside the body whereas the out-of-body scenario replicates a implantable or swallowable wireless device transmitting out of the body. Latter situation is for example encountered in capsule endoscopy applications. Transmission measurements are carried out in the UWB frequency range from 3 GHz to 6 GHz. In an additional experiment, a data transmission evaluation is carried out using an impulse radio UWB transceiver [8]. Its distance dependent bit-error rate performance is tested in the out-of-body scenario.

The influences of the transmitting and receiving antenna are included in the measurements, providing a realistic estimation of the overall link budget. In order to represent a realistic candidate to be integrated in a capsule endoscope, the size of the antennas to be placed inside the body is deliberately kept below 1 cm^2 over the whole frequency range. All measurements are carried out in a homogeneous broadband tissue simulating liquid. Although somewhat simplifying, this approach ensures well-defined and reproducible measurement results.

All scattering parameter measurements were carried out using an Agilent PNA-N N5230A network analyzer. The liquid phantom material used in the measurements is a tissue simulating liquid specified at 3.5 GHz [9]. A broadband measurement of its dielectric properties was performed in order to determine its usability in a wider frequency range. An 85070E coaxial probe kit from Agilent was used for this characterization. In figure 1 the measured phantom properties are compared to the properties of selected human tissues reported in Gabriel et al. [2].

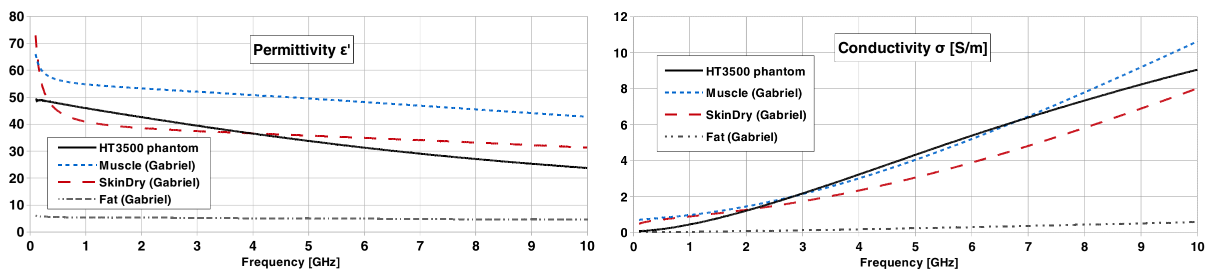

Figure 1: Measured dielectric properties of the liquid phantom [9] compared to the dielectric characteristics of skin, muscle and fat reported in [2].

As shown in Figure 1 the measured dielectric properties can be considered as representing the average dielectric properties of the human body within the UWB frequency range. The measured results will therefore give a good approximation of the attenuation of the signals within a human body. However, detailed simulations have to be used to further investigate the influence of the inhomogeneity of the specific body parts located between the transmitter and the receiver antennas.

The loop antenna used in the phantom consists of a printed planar loop that has been proposed and developed at the Nagoya Institute of Technology [10]. With a diameter of 11 mm this antenna is small enough to fit into ingestible and implantable devices. It is designed to be used in the UWB frequency range, exhibiting best RF matching between 2.7 and 5 GHz while it is immersed in the phantom liquid. In order to avoid the direct contact to the liquid, a thin insulating layer is wrapped around the loop. The S11 scattering parameter measured under these conditions are shown in figure 2. The antenna has also been simulated in SEMCAD X [11].

3. Experimental setup

In-Body scenario: In a first experiment, two exemplars of the in-body loop antennas are placed into the phantom liquid at a depth of 25 mm. The liquid phantom is put into a plastic container that is large enough for the antennas to be surrounded in all directions by at least 10 cm of phantom material. The signal attenuation between the two antennas is measured by the network analyzer. This measurement is repeated for different antenna distances from 20 mm to 60 mm. The loops of the antennas are oriented to face each other.

Out-of-body scenario: In a typical wireless endoscopy setup the receiver is located outside of the body. In contrast to the in-body part, its requirements in terms of form and size are therefore much less strict, allowing for a wide choice of antenna designs. Four different antennas were used at the receiver side in the out-of-body experiment: A circular patch antenna [12], a planar dipole [10], a planar UWB antenna from Fractus [13] and a crude wire loop antenna for comparison.

UWB transceiver experiment: The UWB transceiver test setup [8], [14] operates at a fixed data rate of 10 Mbit/s and is based on impulse radio. The information is modulated using binary frequency shift keying over a frequency band ranging from 3.15 to 3.75 GHz. The signal is thus situated in the frequency range at which the transmitting loop antenna exhibits best impedance matching. The measured power at the transmitter output is approximately -13 dBm. With these settings the UWB transceiver has previously been measured to achieve a BER of 10-3 with a TX-RX path attenuation of 65 dB. The BER is determined using a defined periodic 127 bit pseudo-random binary pattern. This UWB transceiver implementation is used to perform an additional channel evaluation. Based on the out-of-body scenario, the raw bit-error rate (BER) of the wireless link is tested in function of the Antenna distance *d*, giving an estimate of the maximal implant depth that this transceiver can reach. The Fractus antenna is used at the receiver side.

4. Results

Antenna simulation: Preliminary simulations showed a good agreement between the transmission characteristics of the simulated and measured data (figure 2). However, due to the different broadband characteristics of the tissue simulating liquid used in the measurements and the parameters applied in the simulations, the resonance frequency is shifted. Furthermore, the connecting coaxial line is not included in the numerical model. This has to be further enhanced and refined to closely reproduce the measurements.

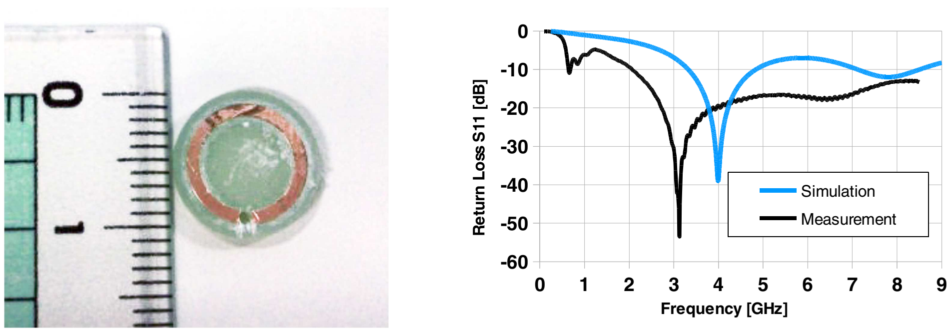

Figure 2: Left: Active element of the loop antenna designed for in-body applications. Right: Simulated and measured reflection coefficient of the antenna while being immersed 15 mm into the phantom liquid.

In-Body scenario: The measured transfer characteristics for five different antenna to antenna distances are shown in figure 3. In general, strong frequency-dependent losses are observed. Frequencies above 4 GHz are attenuated by the medium to such a degree that data communication is only imaginable over distances of less than 3 cm.

Out-of-body scenario: like for the in-body experiment, the observed losses are high and increase steeply towards higher frequencies. At a distance of 8 cm the measured losses are higher than 60 dB throughout the observed frequency range. At the same time, the measured loss at 4 GHz is at least 20 dB worse than the value at 3 GHz, independent of the used antenna type and its orientation. The lowest loss is measured at 3 GHz.

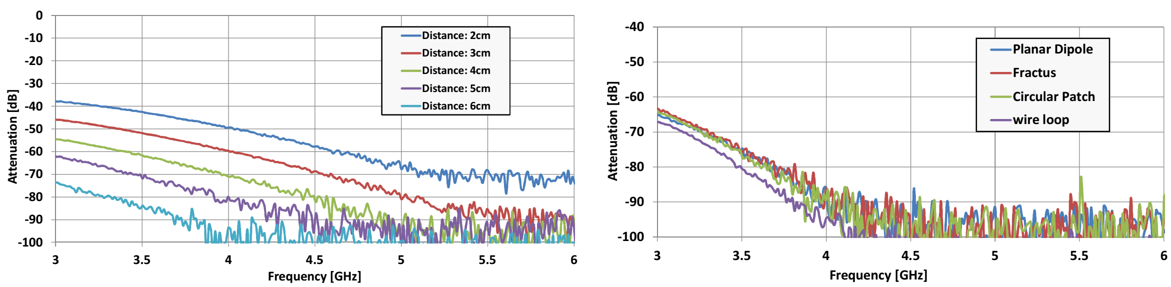

Figure 3: Left: Measured Attenuation for the in-body scenario (left). Right: Results of the in the out-of-body scenario using a transmitter depth of 80 mm (right). The position of the RX antenna orientation was optimized for minimum achievable path loss at 3.3 GHz.

UWB transceiver experiment: The results of the BER measurements are shown in figure 4. A bit-error rate below 10^{-3} can only be achieved if the signal has to travel through less than 6 cm of phantom. The frequency modulation scheme employed in this transceiver has shown to be unsuitable for this communication channel. The digital data is modulated by transmitting pulses on two different carrier frequencies (3.3 GHz and 3.6 GHz respectively). The effect of increasing losses towards higher frequencies is very noticeable and leads to a strongly asymmetrical distribution of the received power between a binary "1" and "0". Even with this moderate 10% relative frequency shift, the observed difference in power was more than 6 dB. The total BER is therefore mainly determined by the attenuation of the higher frequency content.

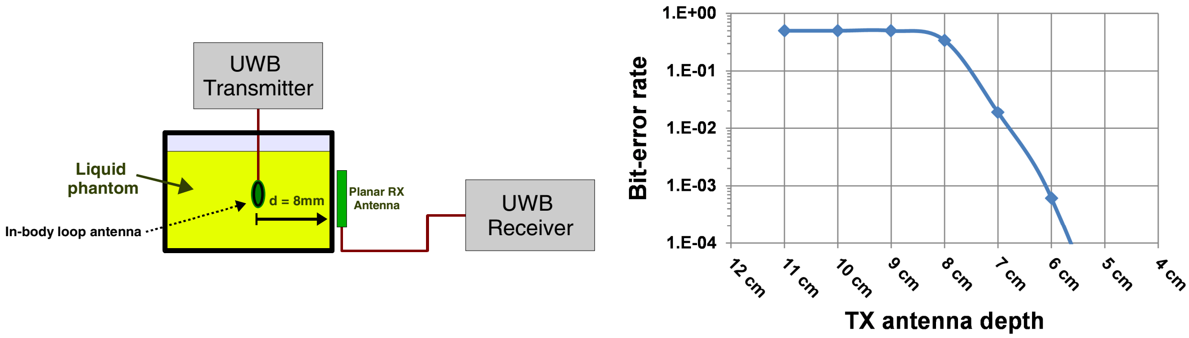

Figure 4: Left: Experimental setup of the UWB transceiver experiment. Right: Bit-error rate measured in the UWB transceiver experiment. This measurement was performed with the Fractus antenna at the receiver side.

5. Conclusion

The experimental results presented here show the limitations of using UWB for in-body applications. For implanted devices situated at a depth of less than 6 cm, UWB is a very promising technology for achieving high data rates. This was successfully verified using an UWB transceiver operating at 10 Mbit/s. Applications requiring longer in-body transmission distances however, e.g. wireless capsule endoscope systems, will often be limited by the large and strongly frequency-dependent transmission losses encountered in biological tissue. Under these circumstances, a communication system is likely to operate in the power limited regime, where additional bandwidth barely improves channel capacity. If UWB is chosen for in-body wireless transmission it is advisable to focus the transmitted power into the low end of the frequency band.

According to the trend of our measurement results, the optimal operating frequency for in-body applications is found below 3 GHz. For a more complete picture the investigation must therefore be extended to a broader frequency range. A further important step includes the modeling of the non-homogeneous properties of the human body.

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