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Enabling Ultrasound In-Body Communication: FIR Channel Models and QAM Experiments

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Abstract—Ultrasound waves pose a promising alternative to the commonly used electromagnetic waves for intra-body communication. This due to the lower ultrasound wave attenuation, the reduced health risks and the reduced external interference. Current state-of-the-art ultrasound designs, however, are limited in their practical in-body deployment and reliability. This stems from their use of bulky, focused transducers, the use of simple modulation schemes or the absence of a realistic test environment and corresponding realistic channel models. Therefore, this work proposes a new, ultrasound, static emulation test bed consisting of small, omnidirectional transducers and custom gelatin phantoms with additional scattering materials. Using this test bed, we investigate different in-body communication scenarios. Multiple communication channels were extracted and mapped onto FIR channel models, which are verified and open sourced for future research. Furthermore, a basic QAM modem was built to assess the communication performance under various modulation schemes. A link was established using 4-QAM and 200kbit/s resulting in a BER $< 1e-4$ at received Eb/No of 13dB. Identical results were obtained by computer simulations on the FIR channels, which makes the extracted FIR channels suitable for the design of future ultrasound in-body communication schemes.

Index Terms—ultrasonic, wireless communication, intra-body communications, channel estimation, ultrasound impulse response, gelatin phantoms, QAM modulation

I. INTRODUCTION

IMPLANTED medical devices (IMDs) aid in the localized diagnosis or treatment of several major diseases such as cardiac pace malfunctioning, hearing problems or diabetes. These devices exhibit an in-body communication link to enable remote monitoring, configuration, control or even real time information sharing [1]. For this, current in-body communication technology relies on electromagnetic (EM) wave propagation [2]. Next generation IMDs, such as the ingestible endoscopic capsule, the retinal prosthesis and closed-loop multi-sensor systems, need to communicate over larger distances, at higher data rates and increased reliability; all within a limited energy budget [1], [2]. These desired specifications are impossible to achieve using EM waves, due to the water-like environment of the human body. As an alternative, ultrasound (US) wave propagation poses the following advantages over EM waves: i) lower wave attenuation in the human body, thus higher

transmission distance; ii) reduced health risk at identical transmitted power intensity; and iii) less interference from undesired external communication sources [3]. Based upon these advantages, recently some ultrasound in-body designs arose, focussing on the PHY level [4], [5], the low-energy implementation [6] or on specific neural applications [7]. A survey on the different in-body communication mechanisms, including capacitive and galvanic coupling, is provided in [1].

The state-of-the-art US in-body designs, however, are limited in their usage in the real human body due to several reasons. The transducers used in [4] and [5] are high-quality, bulky equipment, typically used in non-destructive testing or medical imaging. These transducers exhibit a wide bandwidth, but their cm-size makes them unsuitable for use in e.g. pill-size IMDs. Moreover, these transducers have a directive radiation pattern, which increases the received signal strength when properly aligned, but also makes them unpractical because of the large orientation changes evoked by e.g. organ movements [8]. A better alternative is to use a custom piezoelectric sheet, such as [6] and [7], which is both small in size and less directive radiating. The achieved data rates are however limited, due to the use of simple modulation schemes [6] or backscattering of a small analog sensor signal [7].

The knowledge of the entire in-body US communication channel is also very limited. In [7] the brain tissue is modeled as an 1D homogeneous, lossy medium. A computer simulated basic 2D human arm model is proposed in [9], but not further used. This absence of a good channel characterization results in far-from-optimal US based communication designs.

To alleviate the previously mentioned limitations, this work proposes a more realistic ultrasound in-body emulation test bed, of which channel models are extracted for future research. Furthermore, a QAM communication link is established experimentally to assess the validity of computer-simulation upon these channel models. This approach is summarized in figure 1a. The US test bed transmits and receives the US waveforms via small size, omnidirectional transducers through tissue mimicking material, i.e. the phantom. The estimated channel models are stored in the finite impulse response (FIR) database, which is provided under an open-source model [10].

The paper is organized as follows: Section II presents the static, ultrasound in-body test bed, which is further used in Section III to characterize channel models in varying in-body communication scenarios. Next, Section IV discusses a basic QAM modem to assess the performance of these channels. These results are then compared to experiments in Section V. Conclusions are presented in Section VI.

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Fig. 1. Schematic (left) providing an overview on the channel characterization procedure and the QAM modulation scheme study. The channels are estimated on an ultrasound in-body test bed, where a remote PC respectively uploads and captures any transmitted and received waveform. These electrical signals are converted to ultrasound pressure waves by the small transducers attached to the phantom. This phantom closely mimics the acoustic human body behavior, in combination with the configurable environment. The picture (right) shows the test bed, with an anechoic watertank as phantom environment.

II. REALISTIC ULTRASOUND TEST BED

The more realistic, ultrasound in-body emulation test bed, which is used consistently throughout this paper, is shown both schematically and by picture in figures 1a and 1b. The test bed incorporates the following components: i) the phantom that mimics acoustic human body behavior; ii) the small, omnidirectional ultrasonic transducers that are indifferent to the actual orientation; iii) the configurable communication environment of the phantom, able to test different in-body communication cases; iv) the analog-front-end (AFE) which conditions the received signal; v) the interfacing instruments, i.e. the arbitrary waveform generator (AWG) and the oscilloscope (SCOPE); and vi) the remote PC and USB link which enable the generation and capturing of ultrasound waveform with a PC for further processing. The following paragraphs provide more details on each of the different components of this test bed setup.

A. Gelatin phantom production

The chosen phantom material is gelatin based, which is an established approach in ultrasound imaging phantoms [11]. The desired volume of degassed water is heated and gelatin powder of 13.5 m% is added. Further, two other compounds are included: i) n-propanol 5 vol% to obtain the correct speed of sound; and ii) 2ml/l of a 40% formalin solution to avoid microbial invasion of the gelatin [11].

The phantoms also have different shapes, following a standard rectangular geometry, to later enable the assessment of the influence of communication depth. In all cases the phantom front surface is 40 by 40mm, providing a wide area for the transducer insertion. The phantoms differ in lengths selected from 20, 40 or 80mm. Additionally, a chicken bone is inserted in a number of selected phantoms, to emulate communication channels in the arm, upper torso, etc. These bones were cleaned using subsequently dish washing soap and hydrogen peroxide to aid in the long preservation of the bones. The regular phantom shapes were created by pouring the liquid gelatin inside custom-made Plexiglas molds. After pouring, the phantom molds were stored in the fridge for three days to solidify.

Fig. 2. Pictures of the produced 80mm long phantoms (both in top view), including positioning of the ultrasound transducers (brown circle) and providing a close-up of the transducer (top-left). Some degradation of the ideally flat phantom surface is clearly visible in figure (b).

Two resulting 80mm long phantoms are shown in figure 2, including the transducer positioning as further used in the experiments. The phantoms exhibit a small degradation of the intended flat surface due to the viscous behavior of gelatin over time. This is however considered as an increase in realism.

B. Phantom environment

The produced gelatin phantoms are tested in two different environments, each mimicking a certain in-body communication concept. These concepts are schematically visualized in figure 3:

- *Surface to surface*: the phantom is entirely surrounded by air, which mimics communication from a device located on or just under the skin towards another device located also at the skin. Further referred to the "AIR channel".
- *Implant to implant*: the phantom is entirely submersed in an anechoic tank filled with water, which is additionally sealed at the top water surface. This concept mimics communication of two implants inside the human body. Further referred to the "I2I channel".

In both cases, the transducers are inserted by making a slit inside the phantom at a depth of approx. 5mm. The anechoic watertank is an 35x25x22 cm³ tank, which is coated with the ultrasound absorbing material Aptflex F28. This material ensures a suppression of the ultrasound wave reflections with at least 20dB over the frequencies of interest 0.5-2MHz [12]. This environment mimics the phantom being surrounded by an infinite non-reflecting medium, because of the small difference in acoustic impedance between gelatin and water [11].

Fig. 3. Schematic of the different phantom environments, featuring different in-body communication concepts. The gray box represents the tested phantom; the white dots indicate the transmitter (Tx) and receiver (Rx) positions.

C. Realistic implantable transducers

The ideal ultrasound transducer for a human body implant should have the following five desired properties:

- 1) *Omnidirectional* In realistic human body implants, the transducer orientation is unknown and will vary over time. By consequence, directive transducers might be not receivable when they are accidentally wrongly oriented. As a result, a transducer with an omnidirectional radiation pattern is needed. Real implementations will be limited by the physical housing of the package, an effect which is omitted in this work.
- 2) *Wide bandwidth* To enable a reliable communication scheme with sufficient data rate, the transducer's transfer function needs to exhibit a relatively large bandwidth.
- 3) *Bio-compatible* For inside body use, the transducer casing should be bio-compatible without having a significant effect on its performance.
- 4) *Small size* For the patient's comfort and the limited space inside the human body, bulky transducers should be avoided.
- 5) *Matched to water* To avoid undesired reflections at the transducer surface, the transducer's impedance should be matched to its operating medium.

Commercial transducers often lack one or two of the proposed five ideal properties. For example, the high-quality transducer used in [4] has a wide bandwidth, but is rather bulky and has a narrow directive radiation pattern.

In this work the 2mm crystals from Sonometrics Corp. are adopted as ultrasound transducers [13]. These crystals are widely used for rotation-invariant in-body distance measurements using ultrasound waves [14], and recently a design using OOK communication was reported [15]. For that purpose the crystals are omnidirectional, have a bandwidth of approx. 150 kHz at a center frequency of 1.2MHz, are bio-compatible and are only 2mm large. The center frequency, however, slightly varies with the transducer orientation, which nuances the perfect omnidirectionality of the transducer. This issue can be resolved with techniques such as channel tracking. The transducer's main drawback is the relatively small received signal in response to an incoming acoustic wave. Therefore, a custom receive circuitry is implemented, which is presented in the next section II-D.

D. Receiver analog front-end

A custom analog front-end (AFE) is designed to optimally condition the signals coming from the piezoelectric transducer at the receive side. This circuitry is schematically drawn in

Fig. 4. Analog front-end for the receiving piezoelectric crystal, consisting of: i) fully-differential charge amplifier; ii) conversion to single-ended; and iii) variable gain amplifier.

figure 4. When an acoustic pressure acts on a piezoelectric material, a high-impedance charge signal is generated. This charge signal q_{in} is converted to a low-impedance voltage waveform V_x by the charge amplifier, which is the first stage in the proposed front-end circuitry [16]:

$$\frac{V_x}{q_{in}}(j\omega) = -\frac{R_F \cdot j\omega}{R_F C_F \cdot j\omega + 1} \quad (1)$$

This circuit high-pass filters the signal, where the lower cut off frequency is designed one decade below the transducer's center frequency. At the desired high-pass frequencies, the circuit provides a constant charge-to-voltage conversion factor equal to $1/C_F$. It is also important to note that due to this circuit the long cable connecting the transducer with the receiver board does not influence the transfer function, as all charge flows on the capacitor C_F [16]. This is necessary because the cable impedance changes with cable re-positioning or contact with water.

Via experiments on the crystals, the capacitance value of C_F is chosen to be 100pF. The lower cut-off frequency is set to 100kHz by the feedback resistor value R_F of 15k Ω . Furthermore, the circuitry is made fully differential to cope with electromagnetic interference on the cable, using common mode input resistors R_{CM} of 1k Ω . To further reduce the impact of the critical long receive cable, approx. 0.5m long, a common microphone cable [17] is used for this connection. This approach ensures good conditioning of the high-impedance signal and properly isolates the signal wires from the water.

The succeeding front-end stages convert the signal towards single-ended and provide a variable gain amplifier which allows to optimize the output dynamic range. As a result, the total voltage gain can be scaled between -10dB and +32dB in steps of 6dB. Furthermore, the entire AFE is powered with two supply voltages of +5V and -5V. The interfacing oscilloscope is the Agilent MSO-X 4104A with a maximum sampling rate of 5GS/s. The transmitter crystals are actuated by the function generator Agilent 33622A, capable of transmitting AWG data up to 1GS/s. A remote PC interfaces with the scope and AWG.

III. CHANNEL ESTIMATION

Key in the design of a communication system is to have a good knowledge of the channel through which the transmitted waveforms propagate. This section presents and discusses the communication channels that are extracted from the realistic ultrasound setup, as explained in the previous section II.

Fig. 5. Least-squares FIR estimation principle. The function generator transmits an 1.7Vrms WGN signal (top-left), which propagates through the system, and is recorded by the oscilloscope (top-right). By least-squares estimation of the FIR coefficients, the 2000-taps impulse response of the entire electro-acoustic system from AWG to scope, is found (bottom).

A. Channel characterization principle

The ultrasound communication channel is estimated by least-squares (LS) fitting of an L -taps finite impulse response (FIR) to the transmitted and corresponding received waveforms. Specifically, the transmitted signal is white Gaussian noise (WGN), generated by the remote PC. This approach provides a large immunity to external noise and interference, allows for relative fast channel estimation and is commonly used for acoustic impulse responses, which typically consist out of hundreds of filter taps [18]. Furthermore, the usage of FIR for channel modeling is widely adopted in wireless RF communication channels [19].

Figure 5 shows the details of the least-squares channel estimation. The function generator outputs a WGN waveform with amplitude of 1.7Vrms, which allows to optimally use the available AWG output swing. The oscilloscope in turn acquires the propagated waveform at the receive circuit output, at a duration of three times the WGN time period. This extended duration allows to capture all necessary timing information: the ultrasound propagation delay (10-100 μ s), the transmitted WGN time period (2ms) and the tail of the waveform, present due to reflecting paths. All signals are processed at passband rate, as a consequence of the relative low center frequency of 1.2MHz. The resulting channel includes the entire electro-acoustic system response: the phantom, the transducers, the cables, the AFE and both interfacing instruments.

The estimated FIR parameters are set to a sampling frequency f_s of 5MHz and a number of taps L equal to 2000. These settings avoid aliasing of the transducer's frequency response and allow sufficient filter length to capture the most important waveform reflections. The FIR coefficients are LS estimated as described in [18] (formula 4). To enhance the LS estimation process, the first pulse of the in- and output waveforms are coarsely synchronized in time.

The next sections first present the reference FIR channels as measured in the anechoic watertank, secondly introduce the pure gelatin phantom results and thirdly present the results of the scattering phantoms. The presented material poses an important subset of a more extensive set of obtained FIR channel estimations. All captured FIR channels, complemented with full documentation, are provided open-source in [10].

Fig. 6. Transfer function of the 80mm water channel: the original, unsmoothed spectrum (FIR1 raw) and the smoothed spectrum (FIR1) by application of an 10kHz moving average filter. Two other comparisons are added: i) the 10min-scale stability of the channel (FIR2); and ii) a frequency sweep over the received magnitude (f-sweep).

B. Reference case: anechoic watertank

A reference FIR is obtained by measuring the anechoic watertank without phantom, providing the system response on the infinite, homogeneous water channel. Therefore, the transducers are supported by a custom plate, which is constructed from the absorbing material Aptflex F28 [12]. These plates are fixed by a surrounding metal frame, which allows to set the transducers distance and depth. The reference transfer function of a watertank channel with the transducers spaced 80mm apart is shown in figure 6. The gray curve presents the original, unsmoothed spectrum, while all other curves are smoothed by a 10kHz moving average filter to enhance visualization. Further, figure 6 also compares the time stability of the test bed. Therefore, a second FIR was estimated on an unchanged setup, but 10min delayed in time, showing a very close in-band resemblance. To test the adopted LS-FIR characterization process, a time-consuming frequency sweep of the received magnitude was performed, which closely resembles the previously obtained FIR spectrum. By consequence, this comparison proves the stability of the obtained channel estimations and confirms that the implementation of the least-squares FIR estimation can be considered reliable.

Fig. 7. Impulse responses (top) and corresponding transfer functions (bottom) of the reference water channel with varying propagation distance.

TABLE I
MAIN SPECIFICATIONS OF THE REFERENCE WATER CHANNEL FIRS

$dist$ [mm]	f_C [MHz]	$H(f_C)$ [dB]	BW_{3dB} [kHz]
1	1.13	-8.29	128
20	1.11	-22.4	180
40	1.13	-26.8	108
80	1.16	-33.0	143

Figure 7 elaborates on the reference water channel, by providing the impulse responses and transfer functions at varying propagation distance. In this setup, any rotational effect is canceled out by fixing the transducer's orientation using the supporting plates. As a result, their single changing parameter is the lateral displacement, which increases the path loss due to spherical spreading of the wave. The impulse responses (fig 7-top) mainly consist of a single, main pulse, which is expected due to the anechoic tank effect. The transfer functions (fig 7-bottom) clearly show the distance dependency in the communication band around 1.2MHz. Furthermore, the spectral shape remains approximately constant, with the exception of the 1mm case having large out-of-band spectral content, plausibly due to near field effects of the transducers. The main specifications from the reference water spectra are summarized in table I, including the FFT magnitude at center frequency, $H(f_C)$, and the corresponding 3dB bandwidth, BW_{3dB} . From this, the center frequency is found relative constant around 1.13MHz, and the 3dB bandwidth is derived to be approx. 135kHz.

C. Pure gelatin phantoms

The produced pure gelatin phantoms of different lengths were submersed in the anechoic watertank. A similar behavior as observed in the water case is expected, as the acoustic impedance of gelatin and water are very comparable [11]. The corresponding gelatin transfer functions are shown in figure 8 (solid line), with addition of the water reference curves (dashed line) for comparison. The gelatin phantoms exhibit a similar distance dependency as the water channels. Their spectral shape shows more variation between the different phantoms, resulting in a smaller 3dB bandwidth of approx. 80kHz. Moreover, the center frequency is shifted to 1.19MHz. Both spectral effects might be due to a slight orientation shift

Fig. 8. Transfer function of the submersed gelatin phantoms of varying lengths (solid curves), represented by the implant to implant environment (I2I). The water reference transfer functions of corresponding distances are added for comparison (dashed curves).

Fig. 9. Impulse responses (top) and corresponding transfer functions (bottom) of the 80mm gelatin phantom surrounded by air (red curve). The reference 80mm water channel (blue curve) added for comparison.

of the transducer crystals in between the water and gelatin experiments.

By putting the gelatin phantoms in pure air, the phantom environment which emulates surface to surface communication (fig. 3) is exercised. In this setup, a channel dominated by multipath is expected due to the six fully reflecting gelatin-air boundaries and the low attenuation of the homogeneous gelatin medium [11]. Figure 9 compares both the extracted FIR and transfer function of the 80mm gelatin air and the 80mm reference water channel. Their impulse responses show similar attenuation of the main pulse, but the gelatin air FIR exhibits a significant number of reflections. This effect translates into the spectral domain by closely spaced dips and peaks in the transfer function and to a higher total received signal energy compared to the water case. This multipath behavior can even increase the communication system performance by the use of schemes with equalizers [20], which are capable of capturing more multipath components.

Figure 10 shows the transfer functions for the gelatin air channels with varying propagation lengths. The overall spectral shape remains constant over distance and is complemented by the typical multipath appearance. Furthermore, the spectra show a similar amplitude reduction with distance as seen in the water environment.

Fig. 10. Transfer functions of the gelatin phantoms surrounded by air, with varying phantom lengths.

Fig. 11. Transfer function of the different scattering phantoms, submersed in the anechoic water tank (solid curves), equivalent to the implant to implant case (I2I). The reference water channel added for comparison (dashed curves).

D. Scattering gelatin-bone phantoms

The produced scattering phantoms consist out of gelatin with a chicken bone inserted, in an attempt to increase phantom realism. Bone material reflects the incoming US waveform by approx. -4.6dB and highly attenuates the US propagation by 3.5dB/cm-MHz [21]. Figure 11 presents the transfer functions of the submersed scattering phantoms (solid line), with the addition of the reference water channels (dashed line). The scattering phantoms exhibit some multipath behavior due to bone reflections, although less severe compared to the gelatin air channels. Furthermore, the received in-band magnitude is comparable to water, except for the 40mm bone phantom. This discrepancy is explained as due to the difference in bone shape in both phantoms, the line of sight in the 40mm bone phantom is blocked, while in the 80mm bone phantom not. As a result, the 40mm bone spectrum is relatively more attenuated from its corresponding water reference, compared to the 80mm case.

IV. MODULATION SCHEME STUDY

In order to assess the communication capabilities of the extracted channels, a basic QAM modem is constructed in high-level matlab language. The communication channels are represented by the extracted FIR channels, discussed in the previous section. This approach allows to derive the optimal communication parameters in function of the selected FIR channel: the modulation depth, the symbol rate, etc.

A. Basic QAM modem

The simulated QAM modem is a coherent M-QAM transmit-receive scheme, where the modulation depth M can be varied between 2, 4 or 16. These settings allow to assert the performance of respectively BPSK, QPSK and 16-QAM. The complete QAM modem is sketched in figure 12 and is further explained by its subblocks.

The transmitter first generates an N_b bit long pseudo random binary data stream (PRBS), denoted by m_k . Second, the QAM modulator converts $\log_2(M)$ bit into an M-ary QAM symbol d_k . The QAM constellation is power normalized and Gray encoded. Further, the QAM symbols d_k are pulse shaped with a raised cosine roll off filter $h(t)$ using a roll-off factor r of 0.5 and truncation window of 12 symbols. Upon transmission, a fixed carrier frequency f_C of 1.2MHz and sampling frequency f_S of 5MHz are chosen, based on the previously discussed phantom transfer function characteristics.

Fig. 12. Schematic of the matlab-level simulated basic QAM modem. The transmitter subsequently generates M-ary QAM symbols d_k , applies a raised cosine roll off filter and mixes the signals to passband. The inserted channel $h_{CH}(t)$ is modeled by an FIR channel, as estimated in section III. This channel includes the entire electro-acoustic impulse response (top box). The receiver coherently estimates upon the transmitted QAM symbols by $\hat{d}_k$.

The channel applies the selected 2000-taps FIR filter to the transmitted passband signal $s_P(t)$. This FIR filter includes the entire electro-acoustic system response, i.e. all components in between the waveform generator and oscilloscope (fig 12-top), including transducers, communication medium, receiver circuitry and both interfacing instruments. Furthermore, Gaussian white noise of power density N_o is added to the channel.

The receiver down mixes the received passband signal $r_P(t)$ by a steep Butterworth low-pass filter. Next, the baseband signal is synchronized using cross correlation with the first 150 transmitted symbols. Lastly, the rotation angle is estimated and the QAM symbols are demodulated.

B. Impact of modulation

A first study uses the QAM simulation environment to assess the impact of changing modulation level M and assumes communication through the reference water channel. In this simulation, the transmitted number of bits N_b is 10^4 and the symbol rate D is 100kSymb/s, which fixes the passband bandwidth BW_{PB} to 150kHz: [22] (page 213)

$$BW_{PB} = D \cdot (1 + r) = \frac{R}{\log_2 M} \cdot (1 + r) \quad (2)$$

Where r is the raised cosine roll off factor, equal to 0.5. The additive Gaussian white noise has a -117dB/Hz noise density N_o , which is in correspondence to measurements of the AFE output noise in the anechoic watertank setting.

Figure 13 shows the impact of the modulation level using the 80mm reference water channel. The figure shows both the error vector magnitude (EVM) of the received signals, as well as the observed bit error rate (BER) in function of the received energy per bit per noise density (E_b/N_o) [22]. In both plots, the performance of communication through an ideal Dirac impulse channel with the same amount of noise is added for reference (AWGN channel; dashed line). The symbol rate is fixed to 100kSymb/s, which creates a varying bitrate with the modulation level. The simulation curves clearly exhibit two regions: i) a noise limited region in the middle, where performance closely follows the simulated AWGN channel; and ii) an inter-symbol-interference (ISI) limited region on

Fig. 13. Impact of modulation using the reference 80mm water channel: simulation of EVM (top) and BER (bottom) versus E_b/N_0 . The symbol rate is fixed to 100kSymb/s. A simulated AWGN channel with corresponding modulation level is added for reference (dashed line).

the right, where the EVM remains constant with increasing transmit power. This ISI originates from the bandwidth limited channel and detrimental multipath effects. Higher modulation levels show a broader ISI limited region, due to the larger impact of ISI at more closely packed constellations.

C. Impact of bandwidth

A second study assesses the impact of the passband bandwidth, while fixing the modulation level M to 4. The variation over bandwidth is achieved by varying the symbol rate, which in turn also influences the simulated bitrate (eq. 2). Other QAM parameters are identical to the previous simulation study.

Figure 14 shows the impact of the passband bandwidth using the 80mm reference water channel. At relative small bandwidths, the performance remains identical, where towards higher bandwidth more ISI occurs, leading to a decrease in performance. For the reference water channel and the proposed basic QAM modem an optimal bandwidth of 150kHz is found.

Fig. 14. Impact of passband bandwidth on the reference 80mm water channel: simulation of EVM (top) and BER (bottom) versus E_b/N_0 . The modulation level M is fixed to 4, equal to QPSK.

Fig. 15. Impact of FIR channel type, all 80mm long channels: simulation of EVM (top) and BER (bottom) versus E_b/N_0 . The symbol rate is fixed to 100kSymb/s and modulation level M to 4, equal to QPSK.

D. Impact of channel

A third study discusses the impact of the channel type, while keeping the bandwidth at 150kHz and modulation level at 4. Other QAM parameters are kept identical to the first simulation study. The air channels, however, exhibit a lower noise density N_0 of -125dB/Hz, as observed during the measurement campaign.

Figure 15 presents the simulation results for the previously discussed 80mm long FIR channels. The reference water case performs best, due to its large bandwidth and low multipath behavior. The submersed gelatin channel has a slightly worse performance, and the submersed gelatin-bone channel performs similar to the water case. These results however need to be interpreted carefully, as only a limited number of channels were extracted. The gelatin air channel performs very bad, visualized by an approximately constant EVM level disregard of transmit power. In this type of channel, the symbol rate and thus bandwidth are too large for the present multipath behavior.

V. EXPERIMENTS

Within test bed communication experiments were performed in order to validate the simulation results of previous section. A PC interfaces with the arbitrary function generator and oscilloscope, responsible for generating the Tx waveforms and capturing the Rx output for further EVM and BER analysis. The schematic of figure 12 remains valid for the experimental setup, where the simulation channel (SIM) is now replaced by the real, physical channel highlighted in the top dashed box.

The instrumentation limits the number of symbols to be transmitted to 16kSymb, due to the restricted scope acquisition length and sampling rate. Consequently, all experiments transmit 8000-bit over the channel. It should be noted that if the up and downmixing operations would be shifted to the analog domain, the number of transmitted bits would significantly enlarge. This was however not performed to keep the flexibility of the setup. Furthermore, both instruments were phase locked by an 10MHz low-jitter reference clock with the AWG as master and SCOPE as slave.

Fig. 16. Experiment (markers) versus simulation (solid curves) of the reference water 80mm channel with varying modulation: EVM (top) and BER (bottom) versus E_b/N_0 . The symbol rate is fixed to 100kSymb/s.

Figure 16 compares the QAM performance of the experiments (markers) with the previously discussed simulations (solid curve) of the reference 80mm water channel. A good correspondence between experiment and simulation is found, highlighted by the mean absolute error in EVM of 0.67dB, over the plotted three modulation types. Furthermore, the BPSK and QPSK types exhibit closely resembling BER- E_b/N_0 curves, as is expected by theory [22]. As a result, the extracted FIR channels can be used for future communication simulations, mimicking experimental behavior.

Next, figure 17 provides a comparison of experiments (markers) with simulations (solid curve) for different channel types. Similar to previous simulations, the symbol rate is fixed to 100kSymb/s and the modulation level to 4. The three different curves exhibit a high experiment to simulation correspondence, highlighted by a mean absolute error in EVM of 0.85dB. As previously stated in section IV, the comparison of the channel types needs to be interpreted carefully, as only a limited number of channels were extracted.

Table II compares the obtained results to the state-of-the-art in US in-body communication. The main test bed parameters

Fig. 17. Experiment (markers) versus simulation (solid curves) of the different 80mm long channel: EVM (top) and BER (bottom) versus E_b/N_0 . The symbol rate is fixed to 100kSymb/s and modulation level to 4.

TABLE II
IN-BODY ULTRASOUND COMMUNICATION PERFORMANCE COMPARISON

	[4]	[5]	[6]	This work
transducer	high-Q (x2)	f/3 high-Q (x2)	PZT sheet (IMD) high-Q (EXT) ^a	piezo crystals (x2)
diameter	9.5 mm	20 mm	0.8 mm	2 mm
f_C	5 MHz	5 MHz	2.6 MHz	1.2 MHz
channel	kidney phantom	tissue (pork loin)	tissue	gelatin-bone phantom
distance	10 cm	5.86 cm	6 cm	8 cm
modulation	THSS PPM ^b	QAM	OOK	4-QAM
equalizer	no	DFE + track	no	no
data rate	70-700kbps	5-30 Mbps	95 kbps	200kbps
BER [-]	$< 10^{-6}$	$< 10^{-4}$	$< 10^{-4}$	$< 10^{-4}$
E_b/N_0	19-21dB	-	-	13dB
Tx	SDR ^c + PA	AWG + PA	ASIC	AWG
Rx	SDR + LNA	SCOPE	ASIC	PCB + SCOPE

^aOnly uplink, i.e. from inside (IMD) to outside body (EXT)

^bPulse Position Modulation with Time-Hopping and Spread-Spectrum

^cSoftware Defined Radio platform

are provided, including channel type and distance, transducer type, active diameter and center frequency. Additionally, the integration level of the transmitter and receiver are compared. The work of [5] achieves the highest data rate, using a pair of focused, high-quality transducer types experimented on a piece of dead animal tissue. The work reported in [4] establishes a link over a 10cm kidney phantom channel, by also using high quality, but bulky transducer types. Both transducer types exhibit a narrow directivity pattern, which results in less severe multi path effects and thus better communication performance, but also reduces the practical in-body use as previously discussed. In [6] a fully integrated design is proposed, with custom ASIC and transducer design. The performance is however limited to data rates of 95kbit/s. This work achieves good BER over reasonable distances and E_b/N_0 compared to state-of-the-art, despite the more realistic test bed including small-scale transducers and gelatin-bone phantoms.

VI. CONCLUSION

Current ultrasound in-body communication designs are limited in their practical deployment and reliability due to the use of bulky, focused transducers, the use of relative simple modulation schemes or the absence of a realistic test environment. In order to improve future designs, proper ultrasound in-body channel knowledge is needed. This work presents a new, ultrasound in-body emulation test bed employing omnidirectional transducers, of which different FIR channel models are extracted and further open sourced for future research. Subsequently, these FIR channel models are used in a basic QAM modem simulation, which achieves 200kbit/s with 4-QAM at BER $< 1e-4$ and received E_b/N_0 of 13dB over an 80mm long submersed gelatin phantom channel. Despite the variation among the FIR channels, communication experiments closely fit simulations with an EVM mean absolute error below 1dB over the simulated E_b/N_0 range.

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