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# Data Packet Transmission through Fat Tissue for Wireless Intra-Body Networks

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***Abstract***: This work explores high data rate microwave communication through fat tissue in order to address the wide bandwidth requirements of intra-body area networks. We have designed and carried out experiments on an IEEE 802.15.4 based WBAN prototype by measuring the performance of the fat tissue channel in terms of data packet reception with respect to tissue length and power transmission. This paper proposes and demonstrates a high data rate communication channel through fat tissue using phantom and *ex-vivo* environments. Here, we achieve a data packet reception of approximately 96 % in both environments. The results also show that the received signal strength drops by ~1 dBm per 10 mm in phantom and ~2 dBm per 10 mm in *ex-vivo*. The phantom and *ex-vivo* experimentations validated our approach for high data rate communication through fat tissue for intra-body network applications. The proposed method opens up new opportunities for further research in fat channel communication. This study will contribute to the successful development of high bandwidth wireless intra-body networks that support high data rate implanted, ingested, injected, or worn devices.

***Keywords* — Intra-body communication, microwave, channel characterization, data packet, Software Defined Radio, GNU Radio, *ex-vivo*, phantom.**

## I. INTRODUCTION[1]

INTRA-BODY Area Networks (Intra-BANs) is a key technology that uses the human body as a communication channel to allow implanted devices to exchange information between each other. Recently, there has been a growing interest in biomedical science and networking technology. Many researchers have extensively studied wireless medical devices that can be implanted [1–3], ingested [4–5], injected [6–7] or worn [8–9] as well as communication between such devices. This cross-fertilization improves various applications such as drug infusing and dispensing, artificial heart and heart assist devices, implantable sensors, and control of other artificial organs [10].

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In healthcare monitoring applications, sensor nodes are placed inside the human body and need to communicate with each other. Besides, many applications that require high data rate communication such as cardiac pacemakers [11], implantable cardioverter/defibrillators (ICD) [12] and neuroprosthetics [13] devices now exist in the market. Due to the growth of sensors that require high data rate, the demand of high bandwidth has increased which provides opportunities for researchers to investigate new research areas.

Generally, three different techniques have been used to propagate a signal onto the human body: Galvanic coupling [14–18], capacitive coupling [17–22], and RF links [23–29]. Usually higher frequencies are not suitable for intra-body communication due to the lossy nature of biological tissues [30,31]. On the other hand, low frequencies cannot support high bandwidth. For this reason, researchers have been investigating the possibilities of using different human tissue channels to support low loss microwaves communication. Microwaves are attenuated by the human body due to the high dielectric losses of skin and muscle tissues. For this work, however, we propose the communication through the fat tissue, which offers lower losses for microwave propagation compared to other tissues. We have previously demonstrated the feasibility of using fat tissue as a low loss microwave transmission channel for intra-body communication [32–33]. But, for a successful communication scenario, real data has to be transferred through a given channel. To the best of our knowledge, this work presents the first comprehensive data packet transmission study that uses the fat tissue as a communication channel. Table I summarizes some state of the art intra-body / on-body communication scenarios.

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TABLE I
STATE OF THE ART INTRA-BODY / ON-BODY COMMUNICATION

| Work | Technique | Frequency | Transmission coefficient, $S_{21}$ | Path Loss |
|---|---|---|---|---|
| **[17]** | Galvanic coupling | 40 kHz | - | ~ -39 dB (d=10 cm) |
| **[18]** | Galvanic coupling | 100 kHz | - | ~ -47 dB (d=10 cm) |
| **[30]** | Galvanic coupling | 100 MHz | ~ -37 dB (d=15 cm) | - |
| **[17,18]** | Capacitive coupling | 100 MHz | - | ~ -27 dB (d=15 cm) |
| **[20]** | Capacitive coupling | 10 MHz | ~ -18 dB d=16 cm | - |
| **[21]** | Capacitive coupling | 26 MHz | ~ -32 dB (d=30 cm) | - |
| **[24]** | RF | 403.5 MHz | - | ~ 54 dB (d=10 cm) |
| **[25]** | RF | 915 MHz | -51.4 dB (d=0.5 cm) | - |
| **[26]** | RF | 1 GHz | ~ -56 dB (d=0.75 cm) | - |

*d = transmission distance.

In this work, we conduct extensive studies to demonstrate the possibility of sending data packets through the fat tissue. We present a microwave propagation study in the R-band (frequency range of 1.7 GHz - 2.6 GHz), that overlaps with the Industrial, Scientific, and Medical (ISM) radio frequency band (1.8 GHz and 2.4 GHz) for implant communications. In this work, we develop a model and perform channel measurements to observe the performance of the data packet transmission in a three-layer homogeneous phantom and *ex-vivo* porcine belly tissue, consisting of skin, fat, and muscle tissue.

The remainder of the paper is organized as follows: In Section II, we describe the materials and the methodology of channel propagation, received signal strength and data packet reception. Based on this, the whole experimental setup for both measurements are presented. The results and discussion is given in Section III. Finally, the paper ends with the conclusion.

## II. MATERIALS AND METHODS

### A. Characterization of Propagation Channel

Homogeneous three-layer tissues, consisting of skin, fat, and muscle were used to study the wave propagation and to investigate the dependence of the transmission channel quality on the thickness and the length of the fat tissue. The simulation model was designed in Computer Simulation Technology – CST Microwave Studio Package and has been processed using a time domain solver (http:\www.cst.com\). A three-layer model was prepared and simulated at the R-band frequency range of 1.7 GHz to 2.6 GHz. Fig. 1 demonstrates the concept of using the fat tissue as a communication channel. A transmitter (TX) launches an electromagnetic signal into the fat tissue. The microwave signal travels through the fat tissue and is received at a receiver (RX) located on the opposite side of the fat tissue. The reflection coefficient ($S_{11}$) and transmission coefficient ($S_{21}$) can be recorded at the transmitter and the receiver, respectively.

Moreover, in order to scrutinize the dependence of the transmission channel quality on the thickness and the length of the fat tissue, we designed two simulation models, namely Model A and Model B. Referring to Fig. 2(a), Model A consists of three-layer tissues and is designed with a dimension of 50 mm × 100 mm (width (W) × length (L)). Further, we vary the thickness of the fat ($T_F$) from 10 mm to 35 mm and the muscle thickness ($T_M$) from 20 mm to 45 mm while we fix the skin thickness ($T_S$) at 2 mm to study the behavior of the scattering parameters (S-parameters) according to the thickness variations. We use the bio-tissue models for the skin, the fat, and the muscle from the CST material library to characterize the tissues in the two models.

For Model B as shown in Fig. 2(b), we replace the theoretical CST waveguide ports with two realistic, custom-made waveguide probes. In Model B, the experiments were carried out in two different environments; (1) phantom equivalent tissue and (2) *ex-vivo* tissue. This is to provide the performance benchmark in a realistic environment, which is the human tissue. From a porcine tissue obtained from a local slaughter house, we extracted with the skin, fat, and muscle. For the entire study in Model B, the model consists of 2 mm, 25 mm, and 30 mm thick skin, fat, and muscle, respectively. We vary the signal transmission distance from 20 mm to 100 mm, with a 20 mm step, for the phantom and the *ex-vivo* setups. These distances were chosen based on the distance between several vital organs such as liver–kidney, pancreas–kidney, and liver–heart and also from the experimental models adopted in previous studies [14, 25]. To prove that the fat tissue is a good communication channel compared to the muscle tissue, we compare the results of using the fat tissue as a communication channel against the results obtained when the muscle tissue is used. For both Model A and Model B, we aligned the probe with the muscle layer and repeat the same experiments as for the fat layer.

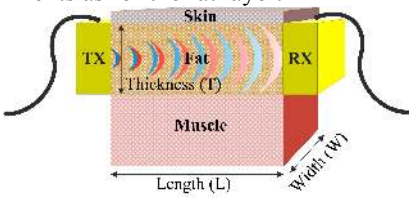


Fig. 1. The concept of channel propagation through the fat tissue.

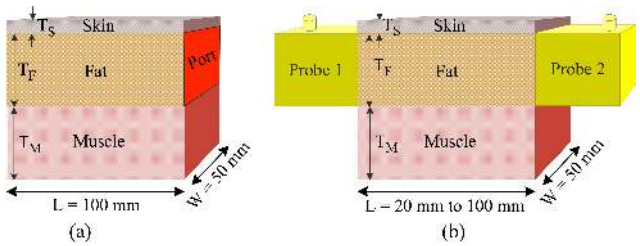


Fig. 2. Two models for the skin-fat-muscle channel.
(a) Model A: Using a theoretical waveguide port.
(b) Model B: Using a realistic waveguide probe.

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Fig. 3 shows the configuration of the probe that we use to launch the microwave signal into the tissue. Each probe consists of a 50 mm × 70 mm × 25 mm rectangular waveguide section, matched to a 50-Ohm coaxial-cable through a topology optimized planar antenna (TOPA) that vertically resides at the center of the waveguide section. The copper distribution over the antenna part is determined by using a recently proposed gradient-based topology optimization method that can efficiently handle tens of thousands of designs variables [34].

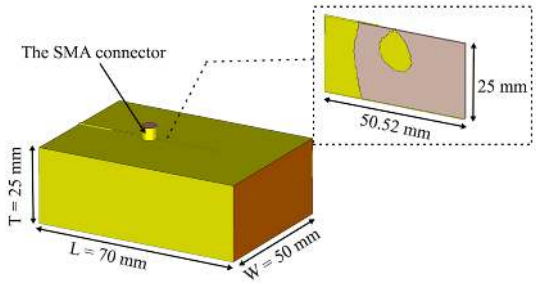


Fig. 3. The configuration of the waveguide probe.

Fig. 4 shows the fabricated probe. The two copper parts comprising the antenna are a radiating lump, connected to the SMA connector, and a back reflector connected to the rear end of the waveguide section to provide proper matching [34]. The prototype antenna is developed using photolithography on a 0.762 mm thick Rogers-3203 dielectric substrate with relative permittivity (ε') of 3.02, loss tangent (tan δ) of 0.016, and a total dimension of 25 mm × 50.52 mm (width × length). The prototype consists of four parts: The planar antenna, the rectangular waveguide section, the fat-equivalent tissue filling the interior of the waveguide section, and the subminiature version A (SMA) connector. The probe-to-probe measurements were taken to set the baseline and to assess the operating frequency [33].

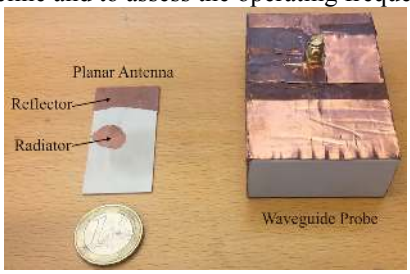


Fig. 4. The topology optimized planar antenna and the rectangular waveguide section [34].

In this pilot study, slight variations that can happen in *ex-vivo* tissue properties are not taken into consideration during measurements. Fig. 5 shows the setup used in characterizing the propagation channel. The dielectric properties for phantom and the *ex-vivo* tissues were measured using an Agilent dielectric slim probe kit (Series number: 85070E) [35]. For each tissue, three measurements were performed in three different locations, and the average value for each tissue was taken. The dielectric properties of the tissue-equivalent phantom and the *ex-vivo* tissues are listed in Table II.

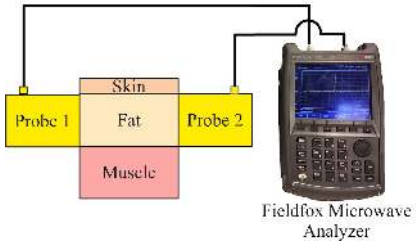


Fig. 5. The setup for the propagation channel measurement.

TABLE II
COMPARISON OF DIELECTRIC PROPERTIES ( ε' AND TAN δ) OF THE PHANTOM, *EX-VIVO*, AND HUMAN AT 2.0 GHZ [36]

| Tissue | Parameter | Material / Environment | | |
|---|---|---|---|---|
| | | Phantom | *Ex-vivo* | Human |
| **Skin** | Relative permittivity | 38.182 | 34.839 | 38.570 |
| | Loss tangent | 0.203 | 0.343 | 0.295 |
| **Fat** | Relative permittivity | 5.038 | 4.096 | 5.328 |
| | Loss tangent | 0.010 | 0.202 | 0.145 |
| **Muscle** | Relative permittivity | 56.114 | 48.855 | 53.290 |
| | Loss tangent | 0.201 | 0.317 | 0.245 |

### *B. Setup Requirement for Data Packet Study*

We used the IEEE 802.15.4 standard for Low-Power Wireless Personal Area Networks (LP-WPANs) [37] physical layer and medium access sub-layer protocols. Specifically, this standard provides specifications for different license-free ISM bands. For the 2.4 GHz ISM band, the standard defines a physical layer with 16 channels spaced every 5 MHz. The data is modulated with Offset Quadrature Phase Shift Keying (O-QPSK) modulation (with half-sine pulse shaping) and transmitted at a resulting data rate of 250 kbps.

In order to increase the robustness of the low-power transmissions, the IEEE 802.15.4 standard uses Direct Sequence Spread Spectrum (DSSS). Each 4-bit data symbol is mapped to a 32-bit long pseudo-random chip sequence, which in turn is modulated using O-QPSK. Since each O-QPSK symbol takes on one of four possible phases [38], it encodes two chips per symbol. The resulting modulated signal has a bandwidth of 2 MHz. The fat channel has an optimal transmission band at 2.0 GHz as can be seen in the Section III. For this reason, we have focused our data packet experiments at 2.0 GHz. Since no standard-compliant 802.15.4 transceiver can operate at 2.0 GHz, we resorted to a software-defined 802.15.4 transceiver.

Our data transmission experiments were performed with the GNU Radio-based 802.15.4 transceiver by Bloessl et al. [39] using a USRP B200 Software Defined Radio (SDR). GNU Radio is an open source development toolkit to implement software-defined radios in a computer. GNU radio provides various signal processing blocks and other tools that, when paired with the appropriate hardware, can be used to implement software radios.

### *C. Data packet reception and received signal strength*

Two separate experimental setups were used to characterize the data packet reception and received signal strength measurements. The experiments were carried out both in phantom and *ex-vivo* environments.

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*Received Signal Strength*

Fig. 6 shows the experimental setup for measuring the received signal strength. The RF TX from the SDR was connected to the Probe 1. The signal propagates through the fat tissue channel and is received at Probe 2. The signal strength is measured with a FieldFox Handheld Microwave Analyzer (Series number: N9918A) [40]. During the measurement, we measure the power received at Probe 2. We obtained the received signal strength by observing the output power at each distance.


Fig. 6. Received signal strength measurement setup.

*Data packet reception*

Fig. 7 shows the experimental setup for both phantom and *ex-vivo* data packet transmission. In this configuration, the USRP device is connected to a host PC via USB. In order to measure the performance of the proposed concept, Probe 1 was connected to the Radio Frequency transmitter (RF TX) port and Probe 2 was connected to the Radio Frequency receiver (RF RX) port. The SDR transmits the packets at 2.0 GHz with 250 kbit/s. For each distance, five measurements were performed with 1000 data packets transmitted for each measurement. The packets were received and analyzed using the Wireshark software. The percentage of data packets received with probe-to-probe measurement is used as a reference. Six different input powers (from -25 dBm to 0 dBm) were demonstrated to identify the optimum power for data transmission. Fig. 8 shows the experimental setup of the two environments. Both experiments have been done in the laboratory at 22 °C (71.6 °F) with 36% relative humidity. A surgical scalpel was used to cut the tissues into their respective dimensions.

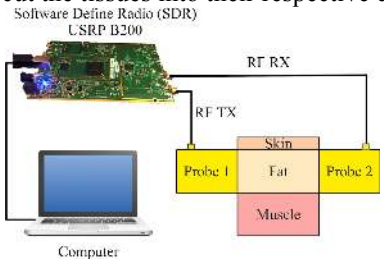


Fig. 7. Experimental setup for packets measurement setups.


Fig. 8. Experimentation setup in (a) Phantom and (b) *Ex-vivo* environments consisting of skin, fat, and muscle layer.

## III. Results and Discussion

### A. Characterization of the Propagation Channel

*The dependence of the transmission channel quality on tissue thickness*

Fig. 9 and Fig. 10 show the effect on the transmission channel quality by varying the thickness of fat and muscle tissues when the waveguide ports are aligned with the fat layer and the muscle layer, respectively.

To study the impact of fat thickness, we fix the skin and muscle thicknesses at 2 mm and 30 mm respectively, while varying the fat thickness by 5 mm from 10 mm to 35 mm. As shown in Fig. 9 (a), the transmission coefficient ($S_{21}$) is improved when the fat tissue thickness increases until 25 mm and it does not improve much when the thickness is increased further. Fig. 9 (b) shows the result under the condition that the muscle tissue thickness is varied by 5 mm from 20 mm to 45 mm, respectively, while the skin and fat thicknesses were fixed at 2 mm and 25 mm. The simulation results show that both amplitudes of $S_{11}$ and $S_{21}$ remained almost constant. Therefore, the signal transmission quality is not affected by the muscle thickness.

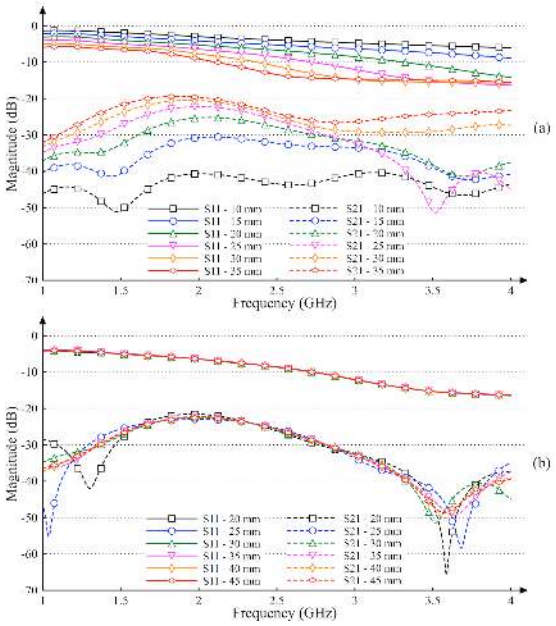


Fig. 9. The effect of the fat tissue thickness on $S_{11}$ and $S_{21}$ from the simulation (a) skin = 2 mm, fat = 10 mm to 35 mm, muscle = 30 mm, (b) skin = 2 mm, fat = 25, muscle = 20 mm to 45 mm. Waveguide port aligned with the fat layer.

Fig. 10 (a) shows the S-parameters simulation results obtained for waveguide ports aligned with the muscle layer while the thickness of fat layer was varied from 10 mm to 35 mm by 5 mm. In Fig. 10 (b), the muscle layer thickness was varied from 20 mm to 45 mm by 5 mm while keeping fat layer thickness fixed at 25 mm. The waveguide ports are aligned with the muscle layer for S-parameters simulation. Fig. 10 (a) and Fig. 10 (b) show that when the waveguide ports are aligned to the muscle layer, there is no substantial variation in the S-parameters with respect to the change in the fat or muscle tissue thickness. Compare the $S_{21}$ from

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Fig. 9 with Fig. 10 at 2.0 GHz, we infer that the magnitude is 10 dB better in the case of waveguide ports aligned with the fat layer than with the muscle layer.

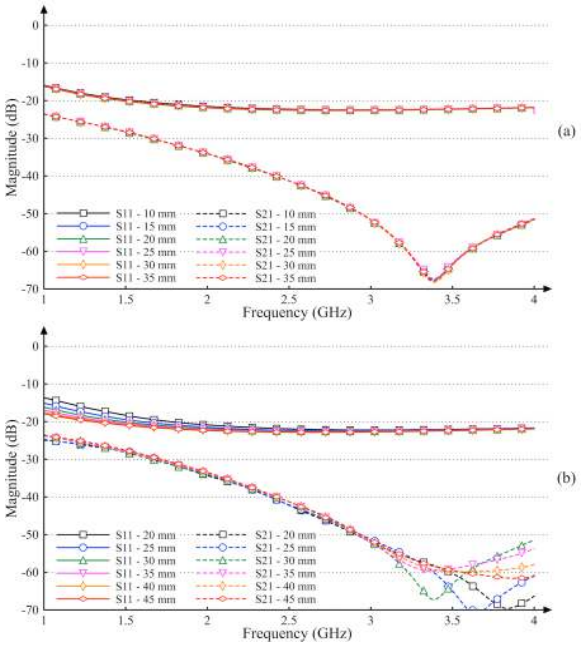


Fig. 10. The effect of the fat tissue thickness on $S_{11}$ and $S_{21}$ from the simulation (a) skin = 2 mm, fat = 10 mm to 35 mm, muscle = 30 mm, (b) skin = 2 mm, fat = 25, muscle = 20 mm to 45 mm. Waveguide port aligned with the muscle layer.

*Comparison with respect to the tissue length*

In order to investigate the influence of the tissue length between the two probes, the corresponding measurement and simulations were carried out. To compare the microwave coupling through the muscle tissue against the coupling through the fat tissue, we repeated the measurement with the probes aligned to the muscle layer. Fig. 11 shows the reflection coefficient ($S_{11}$) comparison between simulation and measurement results. We vary the channel length from 20 mm to 100 mm, with a 20 mm step, for the phantom and the *ex-vivo* experiments. Fig. 11 (a) and Fig. 11 (b) show the $S_{11}$ results when the waveguide ports are aligned with the fat layer and the muscle layer, respectively. The slight disagreement in resonant frequency may have been caused by the positioning of the probes within the three-layer tissues, the variation in dielectric properties, and the losses of the prototype during fabrication. Since our primary focus is on lateral intra-body communication, $S_{21}$ is given special attention.

Fig. 12 shows the $S_{21}$ comparison between simulation and measurement results corresponding to the signal transmission distance varied by 20 mm from 20 mm to 100 mm for phantom and *ex-vivo* environment. Fig. 12 (a) and Fig. 12 (b) show the $S_{21}$ results when the waveguide ports are aligned with the fat layer and the muscle layer, respectively. It can be seen that the simulation results at 2.0 GHz are comparable with the measurement results. According to the results shown in Fig. 12 (a), both the simulation and the measurement show a decrease in the amplitude by ~2 dB per 20 mm for phantom and ~4 dB per 20 mm for *ex-vivo* as the distance between the two probes increases from 20 mm to 100 mm.

Table III shows the $S_{21}$ data extracted from the simulation and measurement at 2.0 GHz. From Table I and Table III, we infer that our proposed fat channel model facilitates better signal coupling compared to existing techniques. Fig. 12 (b) shows that the transmission loss (dB) in the muscle layer is more than two-fold of the transmission loss (dB) through the fat layer as in Fig 12 (a). From Fig. 12, we can conclude that, the fat layer is a better communication channel than the muscle layer.

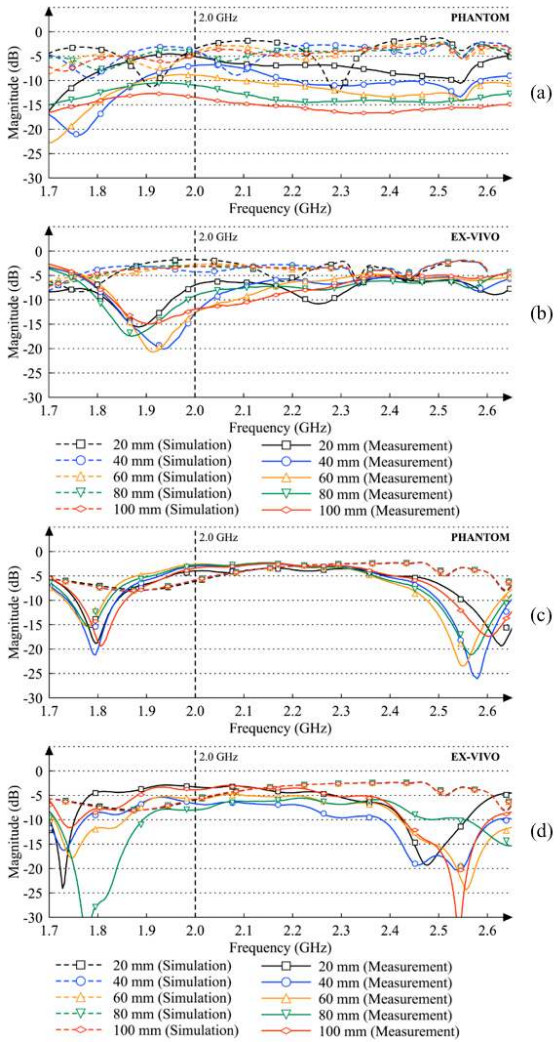


Fig. 11. Reflection coefficient ($S_{11}$) comparison between measurement and simulation results corresponding to the signal transmission distances for phantom and *ex-vivo*. (a) and (b): Probe aligned with the fat layer, (c) and (d): Probe aligned with the muscle layer.

## B. *Received signal strength and data packet reception*

*Received Signal Strength*

In this sub-section, we investigate the minimum transmission power required for a reliable communication. We carry out the experiment to observe the received signal strength (dBm). For the phantom and the *ex-vivo* tissues, we vary the length of the fat-channel from 10 mm to 100 mm with a 10 mm step. The probe-to-probe results determine the baseline of the performance of the communication link.

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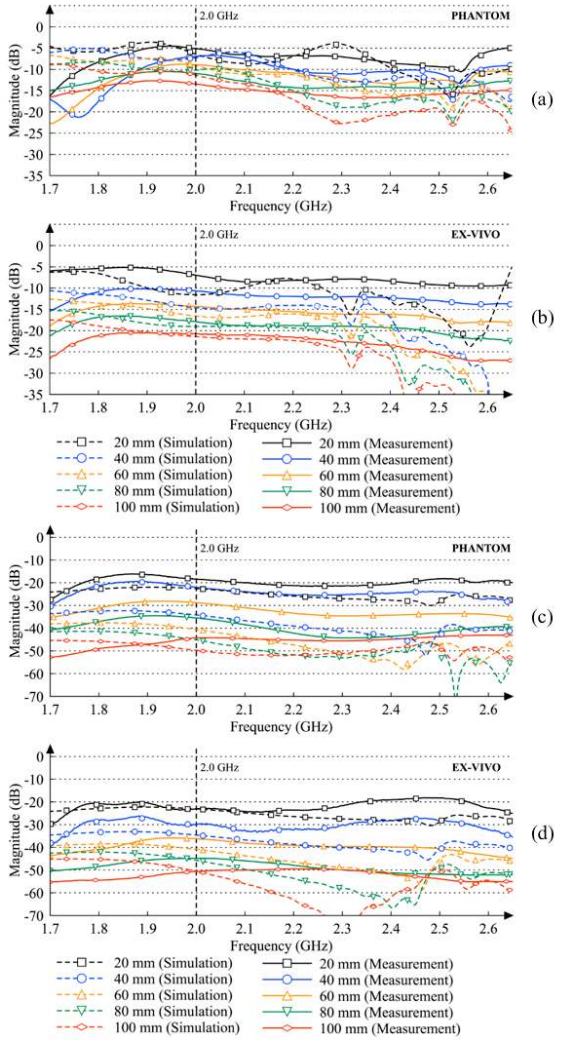


Fig. 12. Transmission coefficient ($S_{21}$) comparison between measurement and simulation results corresponding to the signal transmission distances for phantom and *ex-vivo*. (a) and (b): Probe aligned with the fat layer, (c) and (d): Probe aligned with the muscle layer.

TABLE III
TRANSMISSION COEFFICIENT ($S_{21}$) DATA AT 2 GHZ FOR SIMULATION AND MEASUREMENT (PROBE ALIGNED WITH THE FAT LAYER)

| Distance (mm) | Simulation | | Measurement | |
|---|---|---|---|---|
| | $S_{21}$ (dB) | | $S_{21}$ (dB) | |
| | Phantom | *Ex-vivo* | Phantom | *Ex-vivo* |
| 20 | -6.51 | -11.57 | -5.18 | -7.06 |
| 40 | -7.22 | -14.60 | -6.88 | -10.70 |
| 60 | -9.16 | -16.58 | -8.94 | -14.33 |
| 80 | -10.18 | -19.03 | -11.04 | -17.99 |
| 100 | -11.42 | -21.40 | -13.51 | -20.74 |

We vary the transmission power from -25 dBm to 0 dBm for both environments. The transmission efficiency is defined as the ratio of the received signal strength at the receiver to the transmission power at the transmitter. The solid and dashed lines in Fig. 13 indicate measurements using the three-layer tissue-equivalent phantom and *ex-vivo* tissues, respectively. For both environments, the transmission efficiency is decreased as the distance between the transmitter and receiver is increased. This is because; the coupling between the transmitter and receiver is reduced depending on the distance between them. At 2.0 GHz, the signal strength decreases with ~1 dBm per 10 mm in phantom, while ~2 dBm per 10 mm in *ex-vivo*. The path loss is defined as the ratio of power transmitted ($P_{tr}$) to power received ($P_{rec}$) [41].

$$PL|_{dB} = (P_{tr} / P_{rec}) = - 10 \log_{10} |S_{21}|^2 = - |S_{21}|_{dB} \quad (1)$$

The received power measurement with respect to the three-layer tissue lateral distance is shown in Fig. 13. The probe-to-probe power received is consider as a default path loss of the transceiver system. Therefore, for calculating the channel path loss, the default loss is subtracted from the total path loss for a given channel length. Thus, the average path loss for 10 mm of three-layer phantom and *ex-vivo* tissues calculated using (1) are 1 dB and 2 dB, respectively. Therefore, our proposed fat channel offers low path loss for intra-body communication applications.

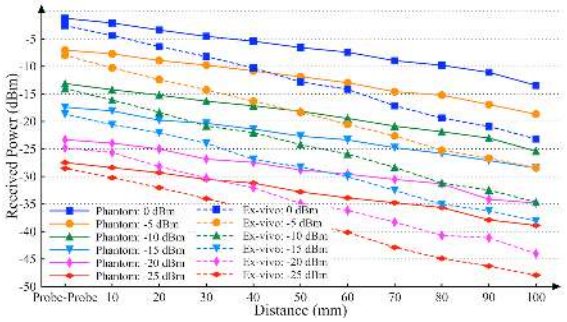


Fig. 13. The received power through the phantom and the *ex-vivo* fat-channels versus the channel length.

*Data packet reception*

We carry out the experiment to observe the percentage of data packet reception with the distance variation. We vary the distance from 20 mm to 100 mm, with a 20 mm step, both for the phantom and the *ex-vivo* tissues. Fig. 14 shows the percentage of packets received for the phantom and the *ex-vivo* at different transmission powers. The error bars show the minimum and the maximum value for each distance. From the bar chart, the average packet reception is approximately 96 % for both phantom and *ex-vivo* experiments. For the phantom, at high transmission power (0 dBm), a substantial increase of reflection occurs at the receiver probe degrading the ongoing transmissions and preventing future data packet reception. Meanwhile, in the *ex-vivo* context, the inherent losses in biological tissue diminish backward reflection and facilitate higher data packet reception. Considering the limitation of SDR, the minimum power level that we have used is -25 dBm even though good packet reception might be possible also at lower transmission powers. Due to the device constraints, currently we are not able to estimate the lower power limit for reliable data packet transmission. Our results show that low transmission power is sufficient. Furthermore, reducing the transmission power will reduce interference on other nodes and may enhance both the overall network throughput and energy consumption [42].

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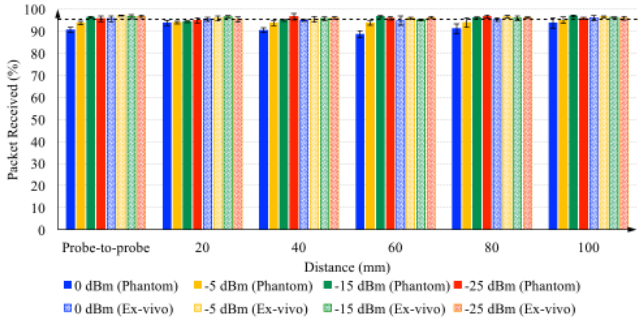


Fig. 14. Percentage of packets received for phantom and *ex-vivo* environments at different transmission power.

As the applications for which the communication model was developed do not require long distances, the range of distance between the transmitter and the receiver was set to 10 mm to 100 mm in our experiments. The measurements presented here demonstrate that reliable data transmission is possible through the porcine fat tissue. The measurements show that the transmission power and receiver sensitivity are important factors for the performance of a communication system. Therefore, there should be an optimal power level for successful data packet transfer and reduction of any possible signal interference that corrupts data packet reception. If the signal is too weak, the receiver cannot correctly receive the transmitted information.

## IV. Conclusion

In this paper, a communication link using a three-layer phantom, *ex-vivo* tissue is simulated and measured. The efficiencies at 2.0 GHz between the transmitter and the receiver were investigated. We designed a high data rate microwave communication link through fat tissue and experimentally demonstrated the performance of the proposed communication using phantom and *ex-vivo* setups. Specifically, we reached data reception up to 96 % for both phantom and *ex-vivo* communication, which may enable intra-body applications requiring high sampling rates such as neural data recording and wireless endoscopic pills. The results show that the signal strength drops by ~1 dBm per 10 mm in phantom and ~2 dBm per 10 mm in *ex-vivo*. The phantom and *ex-vivo* experimentations validated our approach for high data rate communication through fat tissue for intra-body network applications.

To the best of our knowledge, the development of microwave communication through fat tissue is completely original since no similar reports have been found in the literature. Therefore, this work will be beneficial in establishing communication in intra-body area networks. Future work includes the development of an analytical model for the proposed fat channel. The different modulation schemes and IEEE standards in wireless body area networks (WBANs) will be investigated to improve the performance and the efficiency of the system. In the near future, we will also study the effect of embedded muscle, blood vessels, or any other physical disturbances in the fat channel such as body posture, the influence of body dynamics, and the effect of surrounding environment. Since the properties of biological porcine fat tissue are similar to the human fat tissue, we hope that we will be able to demonstrate reliable microwave transmission through human tissue in the future. Ethical approval to conduct clinical trials is under-way. Using human body tissues as communication channel is attractive for a range of futuristic medical applications. This work also has potential application in man-machine interfaces.

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