Conformal In-Body Bolus Antenna for Precision Goat Farming

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***Abstract*—Precision livestock farming has seen an increased interest in the past years. To enable this technology, solid ground work needs to be done to roll-out the system. One major pillar of the ground work is the sensor to base station communication link. In this work, we present an in-body conformal bolus antenna to improve the wireless capability of the sensor nodes, as well in efficiency as in performance. Throughout the paper, we explain the design choices we made based on the state of the art theoretical background that is developed in the recent years concerning in-body antennas. The proposed antenna has a gain of -37.2 dBi. The antenna is well matched to the 50 Ω system and has a bandwidth of 20 MHz.**

***Index Terms*—Conformal Antennas, Internet of Animal Heath, Precision Livestock Farming, In-body**

I. Introduction

In the recent years, a lot of attention was gained for Internet of Animal health (IoAH). This field enables scaling of farms by continuously monitoring the animal and provides the means for precision farming [1]. The framework consists of monitoring the vital parameters of the animal (e.g., by temperature sensors, movement by accelerometers and/or pH-sensors), and is send to a gateway located in the farm by the monitoring device. The gateway sends the information further to the cloud infrastructure were it is analyzed by specialized algorithms. Precision farming can be split in two different use cases; continuous health monitoring on the one hand and performance analysis on the other hand. In the first case, the server infers based on the received data the health of the animal [2]. In case of an abnormal health status, a warning is send to the veterinarian or the farmer. In the latter case, the framework evaluates e.g., training or feeding regiment by correlating the changes with the retrieved data on the cloud [3].

The application of precision farming that we are examining here is the health monitoring of goats in an industrial farm. The sensor is placed in a bolus in the stomach of the goat. A bolus is a common device used in the farming of ruminating stock, e.g. radio-frequency identification (RFID) boluses [4]. The sensor bolus monitors the temperature and the movements of the stomach with the aid of an accelerometer and a temperature sensor. Based on this data, the health of the goat can be monitored 24/7 without the need of the farmer to be present. With specialized machine learning algorithms, embedded and/or remote, the health based on the recorded parameters can be assessed. Once an anomaly is detected, the server sends a warning to the farmer or the veterinarian to quickly intervene. An added benefit of this framework is the possibility that abnormalities can be faster detected than with human on-location monitoring [5]. To enable the IoT solution, many available protocols are available (LoRa, NB-IoT, Sigfox, Wi-Fi, or Bluetooth) [6][7]. The selection upon the technology is based on the available frequency band, the required data rate for the application and accessibility. We chose LoRa in the 434 MHz band after considering the above metrics. The decision of this frequency is discussed in the next paragraph. In this work, we present an in-body conformal bolus antenna to facilitate Internet of Animal Health (IoAH) on a large goat farm. Nikolayev et al. presented insights on in-body antenna design based on the theoretical analysis of the radiation efficiency and loss components of body-implanted antennas [8], [9], [10]. The first challenge of this domain is the complex near-field of the antenna and its high electric losses, which can highly influence the antenna characteristics. The second challenge is the high attenuation of the tissue at the considered frequencies; this could restrict the data rate and the range of the setup. The third challenge is the miniaturization of the antenna because the in-body aspect of the bolus limits the available space considerably. Therefore, complex miniaturization methods will have to be applied. The fourth challenge for in-body bolus antennas is the conformal aspect.

The paper is structured as follows. First, an introduction was given, followed by the discussion on the frequency and the excitation mode of our RF solution. Then, the antenna design is presented and the simulation results are shown. We conclude with an outlook on the next steps in the conclusion.

II. Antenna Design

A. Antenna Environment

Before discussing the antenna design, we investigate at the environment the antenna will be embedded in. The monitoring device is a bolus, a large pill for veterinary medicine. The most common usage is a nutrient bolus or an RFID bolus for identification. In this work, we construct the antenna for a novel sensor bolus: an accelerometer and thermometer collect

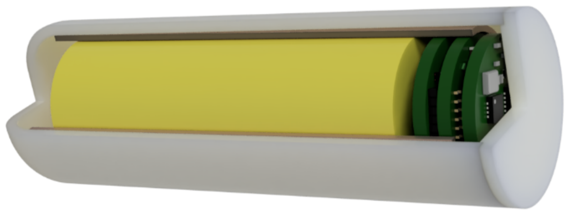


Figure 1: The content of the bolus. The conformal antenna follows the hull of the bolus.

data on the status of the rumen of the goat. This data is relayed to a base station in the barn. The contents of the bolus consist of a battery, microccontroller unit (MCU) board, sensor board, communication logic board and the conformal antenna, as depicted on Figure 1. The exterior of the bolus is bio-compatible alumina (ε_r =10, σ = 0 S/m). The bolus is 7 cm long and has a diameter of 2 cm. Due to the internals (i.e. the battery and the sensor PCBs), the antenna has to be conformal to the shell of the bolus. In its planar form, the antenna has the following dimensions: 60 mm $\times$ 55 mm $\times$ 1 mm. The bolus is placed in the rumen of the goat, see on Figure 2. The bolus is made heavy enough to make it settle on the bottom part of the rumen. This insures that the bolus will not be eructated during the normal ruminating process or be past further in the digestion track. To design the antenna, it is important to know the dielectric properties of the rumen contents. These were measured with the DAK of Speag directly after the slaughter of the goat. This insured that the specimen was on temperature and as close as possible to the in-vivo case. The resulting properties were the relative permittivity ε_r = 73 and and the conductivity σ = 1.5 S/m at 434 MHz at the nominal body temperature of 40 degrees Celsius. For the design phase of the antenna, we assume that the reactive near-field will completely consist of the rumen content. The rest of the goat is assumed to be in the far-field region.

B. Electic vs. Magnetic Antenna

In the early stages of the design process, the question arises which type of antenna we should pick for our solution. The first question is the choice between an electric or a magnetic antenna. As we are dealing with an in-body antenna, the most common choice made in earlier work are magnetic antennas [9]. This is due to the significant lower magnetic loss factor in tissue than its electric counterpart. Yet, in recent work, electric antennas become more popular owing to the effects of dielectric loading by high-permittivity tissues [11]. This is especially of interest for higher frequencies for applications where higher data rate are requested and miniaturization is needed. Despite the high losses, the electric antenna type wins traction in comparison with the magnetic antenna when we consider the miniaturization effect due the dielectric loading. This interplay between higher loss on the one hand and miniaturization on the other hand, results in an optimal choice when choosing the antenna mode type. Based on the permittivity parameters of

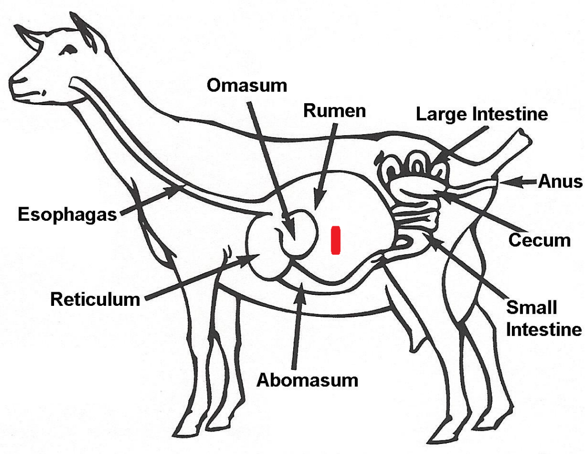


Figure 2: A schematic cross-section of a goat. The red box indicated the predicted place of the bolus after swallowing by the goat.

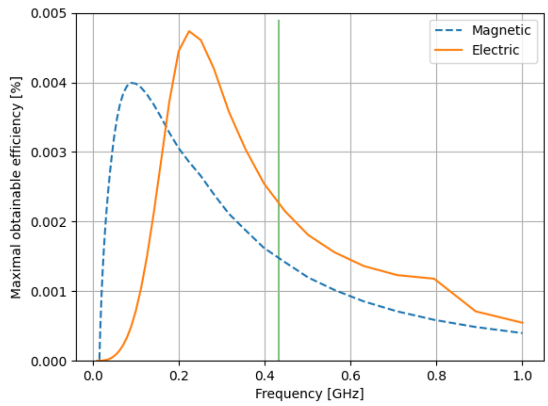
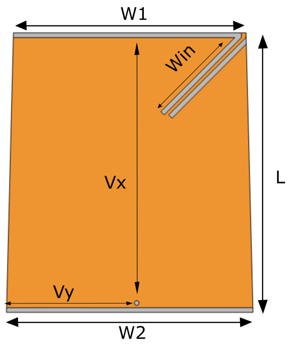


Figure 3: Maximal obtainable radiation efficiency based on the work in [11] and the specified setup parameters. The distinction is made between magnetic and electric excitation mode.The green line indicates the license free 434 MHz band we target in this paper.

the rumen content, the typical dimensions of a rumen, and the dimensions of the bolus, the theoretical maximum achievable radiation efficiency can be determined as described in [11]. Here, the lowest magnetic mode (TE_{10}) is compared to the lowest electrical mode (TM_{10}) induced on a finite cylindrical surfaces representing the radiator following a hull. This shape is exactly the available space for the antenna design in the bolus. Figure 3 shows this maximal radiation efficiency for the investigated configuration. Based upon this comparison, we conclude that an electrical mode excited antenna will provide us the best performing in terms of radiation efficiency ($1.41 \cdot 10^{-3}$% versus $2.15 \cdot 10^{-3}$% at 434 MHz). The IoAH application will be embedded in the LoRa framework. When considering the data rate 136 bps, we can choose between the



(a) Planar Antenna

(b) Conformal

Figure 4: a) the antenna in its planar form with the dimensions denoted: W1 = 53 mm, W2= 50 mm, L = 60 mm, Win = 23.5 mm, Vx = 58 mm, Vy= 28. The angle of the inset is 45 degrees and the transmission line is 1 mm wide. The via has a diameter of 1 mm. The fringing border is 1 mm. b) the antenna in its wrapped up conformal form with curving radius of 10 mm.

434 MHz band and the 868 MHz. As shown in Figure 3, the 434 MHz band has the highest efficiency of the two bands. Figure 3 also shows that an electric mode has a significant higher efficiency (20%) than a magnetic mode. We conclude that the electrical mode antenna is the preferred choice.

C. Antenna Design

In the previous paragraph, we determined that an electrical antenna was the best suited solution for our conformal bolus antenna. The available space is 60 mm $\times$ 55 mm $\times$ 1 mm in its planar form. In the assortment of electrical antennas, we chose the patch antenna. This has the following benefits: it is planar, it is a mature technology and the ground shields the PCB and the battery from the RF front-end. Despite the dielectric loading of the environment, there is still need for miniaturization. Out of the many techniques available in the patch technology, we chose the shorting via [12]. This lowers the resonance frequency by inducing a new mode on the patch. Figure 4a shows that the border to create the fringing field was fixed on 1 mm to make the patch as large as possible, while still enable the fringing mechanism. This left two tuning mechanisms, namely the place of the via and the inset length. Remark that the feeding port is at the border of the patch, and the trapezoid shape is for assembly reasons. For the substrate, Rogers3003 (ε_r = 3, σ = $1.7 \cdot 10^{-5}$ S/m) was chosen for its good radio-frequency performance and material flexibility. The substrate thickness is 0.8 mm, a standard pool size.

For the optimization, a two step approach is used. First, the antenna was brought into resonance at 434 MHz band with the shorting via. Subsequently, the antenna was matched to 50 Ω using the degree of freedom given by the inset.

D. Simulation Setup

The simulations of the antenna were obtained using the FEM solver COMSOL Multiphysics version 5.6 [13]. For the antenna design, the goat's rumen was abstracted to a sphere of 10 cm in radius. The center of the bolus is simulated as air. The ground of the patch antenna will shield the contents of the sensor bolus. A detailed modeling the contents would be an inefficient use of the computational resources. The excitation source was swept from 400 MHz to 500 MHz in steps of 5 MHz. The total simulation domain, including the terminating perfect match layer, is a sphere with a radius of one wavelength in free space, or 0.69 cm. The total number of elements of the mesh was 3938258 tetrahedrals.

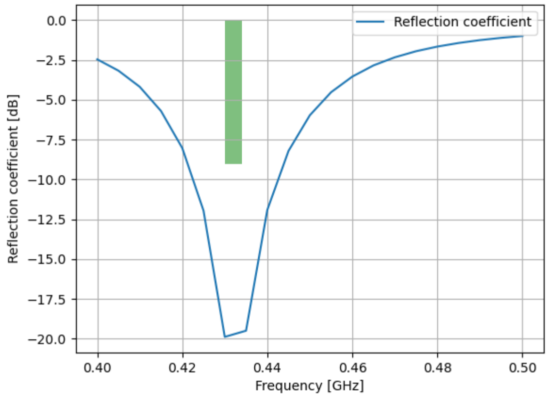


Figure 5: The reflection coefficient of the conformal antenna inside the rumen of the goat (simulated in COMSOL)

III. Results

A. Reflection Coefficient

The results of the reflection coefficient simulation are given in Figure 5. The antenna is well matched for the targeted band ($|S_{11}|$ = -22 dB) of 434 MHz. The bandwidth is 20 MHz (defined by $|S_{11}| < -10$ dB). This good tuning is made possible by the degrees of freedom we could exploit as mentioned in Section II-C.

B. Gain Pattern

Figure 6 shows the gain pattern. The gain is omnidirectional. The maximal gain is -37.3 dBi. This is a good performance considering the deep implantation depth of the antenna (10 cm) inside a lossy medium. The radiation efficiency drops exponential by the implantation depth as mentioned in [11]. Table IV presented in [14], shows that our antenna is in line with the expected performance of state of the art in-body antennas.

IV. Conclusion and Future Work

In this work, we investigated an in-body bolus antenna conformal to the hull of the bolus. This bolus establishes a communication link, connecting the harsh environment of the rumen of a goat to a base station. During the design of the antenna, we applied various techniques where we motivated our choices based on previous work done on in-body antenna design. Ultimately, we constructed an antenna with a maximal

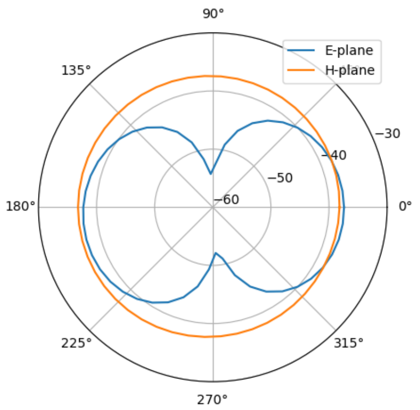


Figure 6: The gain of the antenna in dBi.

gain of -37.3 dBi and was well matched to a 50 Ω system ($|\Gamma|$ = -22 dB) and with a bandwidth of 20 MHz. This is more than sufficient to service the LoRa protocol in the 434 MHz band.

Future work includes assembling the bolus and perform *in vitro* phantom tests to validate the simulations. Then, the bolus will be inserted in a real life goat and the performance will be validated *in vivo*. The complete work will provide a solid backbone for base station planning to roll-out the IoAH system.

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