This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2021.3060501, IEEE Transactions on Antennas and Propagation

Communication

Propagation-loss Characterization for Livestock Implantables at 433, 868, and 1400 MHz

Said Benaissa, *Member, IEEE,* Leen Verloock, Denys Nikolayev, *Member, IEEE,* Margot Deruyck, Günter Vermeeren, Luc Martens, *Member, IEEE,* Jan Govaere, Frank Tuyttens, Bart Sonck, David Plets, *Member, IEEE,* Wout Joseph, *Senior Member, IEEE*

***Abstract*—Automated systems based on wearable sensors for livestock monitoring are becoming increasingly popular. Specifically, wireless in-body sensors could yield relevant data such as ruminal temperature. The collection of such data requires an accurate characterization of the in-to-out body wireless channel between the in-body sensor and the gateway. The aim of this study is to experimentally characterize the in-to-out-body propagation loss for cows and horses at 433, 868, and 1400 MHz. Measurements were conducted *in vivo* on five different fistulated cows and five horse cadavers using specialized robust in-body capsule antennas inside the animals' abdomen. Next, the in-body antenna gain was de-embedded from the wireless channel, and the in-to-out body propagation loss was obtained as the difference between measured unobstructed line-of-sight path losses and in-to-out-body path losses. The measurements showed a body propagation loss of (mean±standard deviation) 30.8±4.1 dB, 44.5±4.8 dB, 54.2±4.7 dB for cows at 433, 868, and 1400 MHz, respectively. For horses, the body propagation losses were 23.2±3.8 dB, 31.0±4.7 dB, and 44.4±3.2 dB at 433, 868, and 1400 MHz, respectively. These results are important to determine the wireless range of WBANs to optimize the network topology and estimate the associated network cost for large-scale monitoring systems.**

***Index Terms*—In-to-out-body path loss, cow, horse, capsule antenna, in-body, body loss, internet-of-animals, link budget, propagation, radio channel.**

I. Introduction

MONITORING systems based on Wireless Body Area Networks (WBANs) and Internet-of-Things (IoT) technology are becoming popular for health tracking of humans and animals. In [1], a review of the applications of WBANs and IoT for human health monitoring is presented. By using this technology, doctors can remotely track the physiological parameters and health status of patients, recommend and fine-tune suitable treatment and medications.

This work was supported by the EOS project MULti-Service WIreless NETwork (MUSE-WINET).*(Corresponding author: Said Benaissa.)*

S. Benaissa, L. Verloock, M. Deruyck, G. Vermeeren, L. Martens, and W. Joseph are with the Department of Information Technology, Ghent University/imec, iGent-Technologiepark 126, 9052 Ghent, Belgium (e-mail: wout.joseph@ugent.be)

S. Benaissa, F.A.M. Tuyttens, and B. Sonck are with Flanders Research Institute for Agriculture, Fisheries and Food (ILVO), Scheldeweg 68, 9090 Melle, Belgium (e-mail: bart.sonck@ilvo.vlaanderen.be)

D. Nikolayev was with the Microwave and Antenna Group (MAG), École Polytechnique Fédérale de Lausanne (ÉPFL), CH-1015 Lausanne, Switzerland. He is now with the Univ Rennes, CNRS, Institut d'Électronique et de Télécommunications de Rennes, UMR–6164, FR-35000 Rennes, France (e-mail: d@deniq.com).

J. Govaere is with the Faculty of Veterinary Medicine, Department of Obstetrics, reproduction and herd health, Ghent University, Salisburylaan 133, 9820 Merelbeke, Belgium (e-mail: jan.govaere@ugent.be)

WBANs and IoT are also employed for health tracking of livestock, such as dairy cows and horses. For instance, sensor-based monitoring systems are used for cows to enhance milk productivity, health, and cow welfare [2], [3]. Such automatic monitoring systems help farmers to detect calving events [4], [5], estrus [6], [7], and diseases, such as mastitis [8] and lameness [9]. On the other hand, WBANs and IoT sensors are used for tracking horses' activity [10]–[12] and detecting diseases [13]. Equipping livestock with a WBAN allows for real-time tracking and analysis of multiple health parameters: e.g., temperature, activity, and location. Consequently, an automatic assessment of the health of the animals are made and alerts are sent to the farm manager to take the needed actions.

Besides on-body sensors (e.g. leg-, ear, tail, or neck-mounted sensors), relevant data (ruminal temperature, pH, etc.) could also be obtained using in-body sensors (e.g. bolus) [14]. Electronic boluses are becoming popular devices for yielding in-body data as, for instance, the rumen pH and temperature [15]. In practice, existing boluses operate by storing the measured physiological parameters and then wirelessly transmitting the stored data to a nearby gateway at regular time intervals (e.g., every two hours). The reliability of the in-to-out body wireless connection between the in-body sensor and the gateway is crucial for real-time tracking of the in-body data and, therefore, well-being of animals. Moreover, a solid understanding of the in-to-out body loss would give insights on the optimal network topology and associated network cost for large-scale in-body animal monitoring systems.

The on- and off-body wireless propagation for WBANs and IoT applications for animals have been investigated in several studies [16]–[18]. For the in-to-out body propagation for animals, studies were conducted on pigs and rats [19]–[23] as listed in Table I. These studies were performed at higher frequency bands (e.g., 3-6 GHz), which may not be suitable for in-body applications. However, to the best of the authors' knowledge, the propagation for the in-to-out-body wireless link has not been investigated yet for dairy cows and horses at 433, 868, and 1400 MHz. The choice of these frequencies is motivated by the studies on the optimal frequencies for in-body applications [24]. Moreover, these frequencies are used by most of the technologies enabling IoT and WBANs (e.g., LoRa [25], Sigfox [26], MedRadio [27]). The methodology used in this paper was described in [28] to characterize in vivo the in-to-out body propagation for cows at 433 MHz. The current study extends the previous one by performing

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2021.3060501, IEEE Transactions on Antennas and Propagation

TABLE I
OVERVIEW OF THE STUDIES CONDUCTED FOR THE IN-TO-OUT BODY PROPAGATION FOR ANIMALS COMPARED TO THE CURRENT STUDY.

Reference	Subjects	Frequency band
[19]	2 Pigs	1-6 GHz
[20]	1 Pig	3-6 GHz
[21]	1 Pig	2.4 GHz
[22]	1 Pig	401, 2450 MHz
[23]	3 Rats	402-405, 2400 MHz
[28]	7 Cows	433 MHz
This study	5 Cows and 5 horses	433, 868, 1400 MHz

measurements on multiple animals (i.e., cows and horses) at different frequency bands (i.e., 433, 868, and 1400 MHz) using novel in-body antennas specifically designed for such applications. Therefore, the objectives and novelties of this study are: 1) experimental characterization of the in-to-out body propagation loss for five different dairy cows and horses at 433, 868, and 1400 MHz; 2) numerical and experimental study of in-body antenna radiation performance to increase the accuracy of propagation loss analysis; 3) application of the obtained results to the derivation of de-embedded body loss.

II. Materials and Methods

A. *Experiment Environments and Animals*

Measurements with the cows were conducted at the Flanders Research Institute for Agricultural, Fisheries and Food (ILVO) in Melle, Belgium (see [16] and [28] for more details about the barn and the measurement area). Five different fistulated (i.e. cows that have been surgically fitted with a cannula [29]) Holstein dairy cows (parity 2.8±1.3) were used. The cows remained at a fixed position for about three hours (measurement time per cow) and were housed individually in the considered area as shown in Fig. 3a.

The measurements with horses were carried out in the animal autopsy division at the Faculty of Veterinary Medicine at Ghent University, Merelbeke, Belgium. Five cadavers of adult horses were used (2 males and 3 females). The path loss measurements were conducted outdoor. A forklift truck was used to mount a horse cadaver at a fixed position as shown in Fig. 3b. The forks of the forklift were positioned as far as possible from the antenna.

B. *In-Body Capsule Antenna*

The design of the antennas is out of scope of the current paper. More details about the design of the three antennas can be found in [30]. The radiation performance was characterized using far-field illumination in a fully anechoic chamber [31]. To account for the effect of tissue, the antenna was centered inside of a ⌀100-mm spherical glass jar containing a muscle-equivalent phantom (the details of the experimental setup are provided in [30]). A muscle-equivalent liquid phantom was prepared for each operating frequency. To achieve the target EM properties, a water–sucrose–salt formula was chosen. To define the concentration of each ingredient, a full factorial experiment design along with the response surface optimization approach was used. The final concentrations of sucrose and salt (NaCl) were, respectively: 51.3%, 1.53% for 433 MHz, 47.5%, 0.31% for 868 MHz, and 43.7%, 0% for 1400 MHz. The achieved EM properties closely match the target ones [32], with the exception of the conductivity at 1400 MHz: $\varepsilon_r = 57$, $\sigma = 0.8$ (S/m) at 433 MHz, $\varepsilon_r = 55$ $\sigma = 0.93$ (S/m) at 868 MHz, and $\varepsilon_r = 54$, $\sigma = 1.6$ (S/m) at 1400 MHz. The higher conductivity at 1400 MHz (target $\sigma = 1.14$ S/m) is attributed to lossy dispersive EM properties of sucrose. Increased conductivity results in slight increase of BW for the measured result (Fig. 2c).

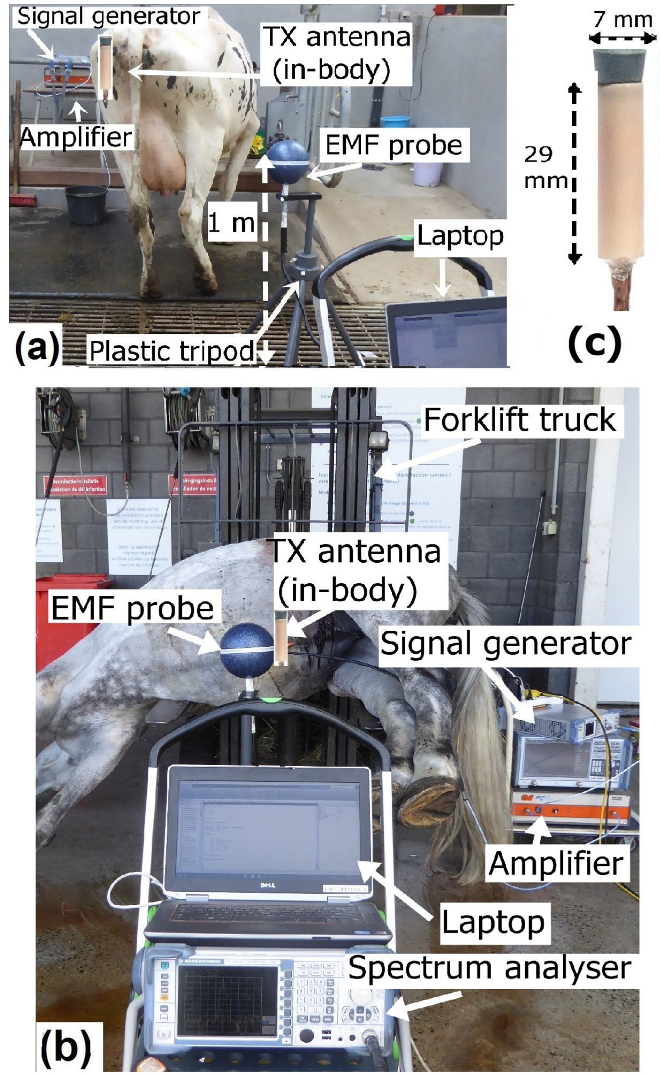

Fig. 1. Setup for the (a) cow and (b) horse measurements. (c) The capsule antenna after the preparation for the measurements (see [30] for more details).

CST Microwave Studio 2018 [33] was used for the numerical design and optimization. A detailed description of the numerical approach is given in [34]. Figs. 2a–c show the impedance characteristics of the capsule antennas in the muscle-equivalent environment and in free space. The -10 dB bandwidths in the muscle-equivalent environment are 39 MHz, 90 MHz, and 124 MHz for 433, 868, and 1400 MHz designs, respectively. The obtained bandwidths fully cover the relevant bands of wireless communication standards such as MedRadio (433 MHz), LoRa (433 MHz, 868 MHz), Sigfox (433 MHz,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2021.3060501, IEEE Transactions on Antennas and Propagation

868 MHz), etc. The $|S_{11}|$ in free space are around -4.5 dB since the antennas were specifically designed for in-body applications.

To derive the measured antenna gain, the gain substitution technique was used. A reference antenna of a known gain [35] substituted the capsule antenna, and the measured gain of the reference antenna was used to calibrate the results. To ensure that cable radiation was not a major contributor to perceived radiation performance, the following techniques were used: 1) low-permittivity dielectric insulation (rubber) of the cable inside of the muscle-equivalent environment and the animals and 2) ensuring placement of the antenna in a way that its polarization is normal to the cable. Moreover, considering the dielectric loading $\varepsilon_r \approx 80$ (capsule shell and filling [30]), the antennas do not classify anymore as electrically small specifications. Specifically, at 433 MHz (the lowest frequency) for $\varepsilon_r \approx 80$, $\lambda/4 = 19.2$ mm, which is comparable to the antenna length of 20 mm [30]. Figs. 2d–f show the far-field characterization results. The maximum measured realized gains in ⌀100-mm spherical phantoms are -28.0 dBi for 433 MHz, -16.0 dBi for 868 MHz, and -16.1 dBi for 1400 MHz. The measured radiation patterns and maximum gain values are consistent with the simulated ones and are close to the fundamental limitations on radiation efficiency [30], [36]. Note that the operating frequencies of 868 MHz and 1400 MHz are within the optimal range for the 100-mm spherical phantom, which explains higher gain values at these frequencies compared to 433 MHz. In free space, the maximum simulated gains (dipole-like radiation patterns) are -43.9 dBi, -34.5 dBi, and -28.7 dBi for 433, 868, 1400 MHz, respectively. The low realized gain in free space is due to the mismatch in air ($|S_{11}| \approx -4.5$ dB) and reduction of dielectric loading. Note that the in-body antenna accounts for dielectric loading by tissues to achieve both improved radiation performance and impedance matching [37]. The measurement errors are within the usual range for in-body antennas and are attributed to the manufacturing and assembly tolerances, imprecision in EM properties of the phantom and capsule materials, and uncertainties of the antenna placement inside of the phantom. The presented antenna gain values in this section were used for the de-embedded path loss calculation (Section II-D). The S_{11} of each antenna was measured once it was implanted in the animals (See an example in Fig. 3). Although the value of the S_{11} at the central frequency varied between animals, it remained under -10 dB for all animals and frequencies, ensuring a minimal effect of the mismatching on the obtained propagation loss.

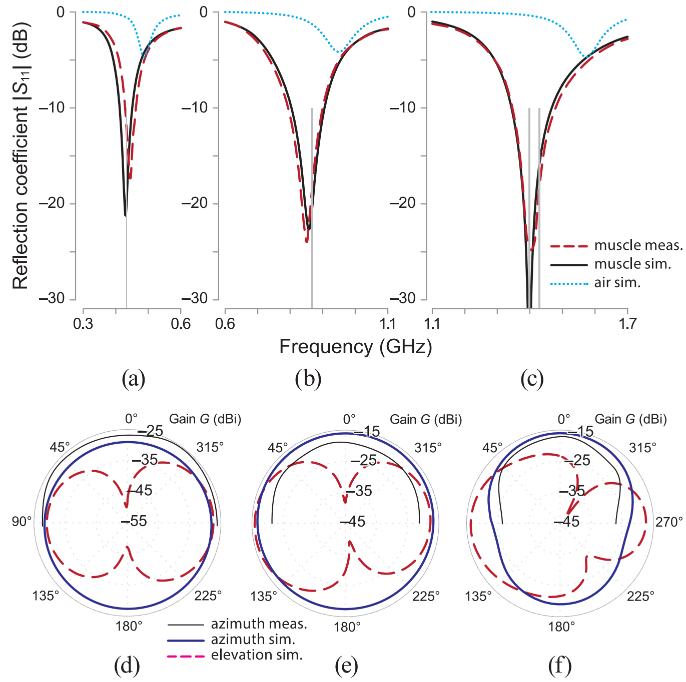

Fig. 2. (a)–(c) The reflection coefficient $|S_{11}|$ in free space and in a phantom with muscle-equivalent EM properties (in-body). (d)–(f) Measured and computed radiation patterns in a ⌀100-mm spherical phantom with muscle-equivalent properties.

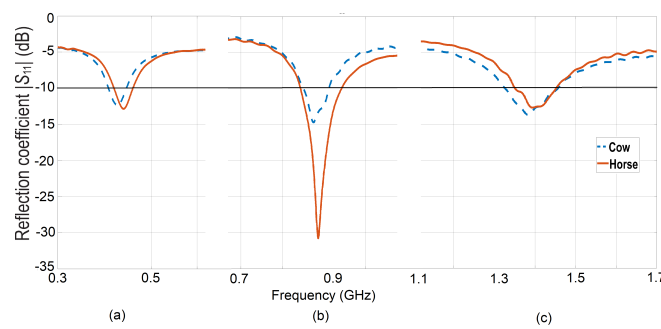

Fig. 3. Example of the measured reflection coefficient $|S_{11}|$ once the antenna was implanted in the animals. (a) 433-MHz antenna, (b) 868-MHz antenna (c) 1400-MHz antenna.

C. Path Loss Measurement Scenarios

The setup of the path loss measurements for cows and horses is shown in Figs. 1a, 1b. Similar to [28], the transmitter part consists of a transmitting antenna (TX), an amplifier, and a signal generator (Rohde & Schwarz SMB100A, 100 kHz–12.75 GHz). Fig. 1c shows the antenna prepared for the measurements. For the cows, the TX antenna was placed in the rumen bottom of the fistulated cow. The separation from the antenna to the outside was 25 cm (length of the RF cable inside the body). For the horse cadaver, the TX antenna was placed by a veterinarian close to the horse stomach at about 20 cm depth. The horse cadaver was mounted with a forklift truck at a height of 1 m (horse stomach to ground). The power injected to the antenna was 32 dBm (maximum power that can be generated). For both animals, the transmitting antenna was placed such that the maximum radiation is oriented towards the receiving antenna.

The receiver (RX) part was the same as in [28] (EMF probe connected to a spectrum analyzer). The received power was measured for different TX–RX separations (1 to 20 m). The mean value (in dBm) of the recorded samples (300 at each measurement location) was considered as the received power for the corresponding TX–RX separation. The measurements were repeated in the same environments but without animals to quantify the increase of path loss due to the body of the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2021.3060501, IEEE Transactions on Antennas and Propagation

animals [28].

D. Joint Antenna-Channel: Path Loss Difference for Body Loss Estimation

From the measured average received power P_{RX} (dBm) for a given TX–RX distance, the path loss PL (dB) without body was calculated as follows:

$$PL_{no\,body} = P_{TX} + G_{TX_{FS}} - L_{TX} + G_{RX} - L_{RX} - P_{RX} \quad (1)$$

where P_{TX} is the transmitter power (dBm) (input power to the antenna), $G_{TX_{FS}}$ the transmitter antenna realized gain (dBi) in free space (Section II-B), L_{TX} the transmitter cable losses (dB), G_{RX} the receiver antenna realized gain (dBi), and L_{RX} the receiver cable losses (dB).

As reported in [16], the path loss equation given by (1) cannot be directly applied to WBANs due to the body-antenna interaction. For WBANs, the antenna gains are generally included in the path loss calculation as follows ([38], [39]):

$$PL_{incl} = P_{TX} - L_{TX} - L_{RX} - P_{RX} \quad (2)$$

However, the calculated path loss values are specific for the used antenna type. Therefore, several studies were aimed at establishing the *antenna de-embedded* path loss [41]–[44]. In this paper, the antenna gains provided in Section II-B are used to derive antenna de-embedded path loss values as follows:

$$PL_{body} = P_{TX} + G_{TX_b} - L_{TX} + G_{RX} - L_{RX} - P_{RX} \quad (3)$$

with G_{TX_b} is the in-body antenna gain of the TX antenna. Finally, the in-to-out body loss could be calculated as follows:

$$\delta_{PL} = PL_{body} - PL_{no\,body} \quad (4)$$

III. Results and discussion

A. In-to-Out Body Loss in Cows

Figure 3 shows a box plot of the body loss at 433, 868, and 1400 MHz for each individual cow (Fig. 3a) as well as the average over all cows (Fig. 3c). The corresponding values are listed in Table II. At 433 MHz, the body loss (mean±standard deviation) varied between 25.6±5.1 dB for cow 5 and 36.6±6.8 dB for cow 1, with an average (all cows) of 30.8±4.1 dB. Higher values were obtained at 868 MHz, with a minimum value of 41.5±4.9 dB (cow 1), a maximum value of 49.3±7.5 dB (cow 5) and an average of 44.5±4.8 dB. As expected, higher body loss values were obtained at 1400 MHz with an average of 54.2±4.7 dB. The variation within cows could be explained by the difference in the quantities of feed in the cows' rumen. Also, the position of the antenna and the distance to the animal's skin may change during the experiment. Note that these values quantify the real loss in power due to cow body (in-to-out-body antenna de-embedded path loss).

TABLE II
Mean, median, and standard deviation (SD) of the in-to-out body loss for each individual cow and horse as well as for all cows and all horses (AVG).

		Freq (MHz)	Subjects 1	2	3	4	5	AVG
Cows	Mean (dB)	433	36.6	30.2	34.2	27.2	25.6	30.8
		868	41.5	46.8	37.6	47.2	49.3	44.5
		1400	51.7	57.3	46.8	60.4	54.9	54.2
	Median (dB)	433	38.9	31.0	35.2	27.2	24.2	31.3
		868	41.9	46.6	37.3	45.7	47.4	43.9
		1400	51.6	57.0	46.0	62.2	54.7	54.0
	SD (dB)	433	6.8	3.4	4.7	4.2	5.1	4.1
		868	4.9	5.7	4.9	6.0	7.5	4.8
		1400	5.5	5.3	5.6	8.4	4.9	4.7
Horses	Mean (dB)	433	28.2	18.9	15.2	31.6	22.3	23.2
		868	31.5	24.1	32.2	36.8	30.6	31.0
		1400	42.1	43	47.8	42.9	46.4	44.4
	Median (dB)	433	27.8	18.1	16.0	30.9	22.2	23.0
		868	32.9	25.3	34.4	38.2	32.2	31.9
		1400	41.8	43.2	47.6	42.7	45.9	44.4
	SD (dB)	433	4.8	4.4	2.8	5.1	4.1	3.8
		868	5.4	4.8	6.5	5.6	3.6	4.7
		1400	4.8	3.2	3.5	3.6	5.7	3.2

B. In-to-Out Body Loss in Horses

The obtained body loss for each individual horse at 433, 868, and 1400 MHz is shown in Fig. 3b. The average over all horses is shown in Fig. 3c. The lowest values were obtained at 433 MHz, with a minimum value of 15.2±2.8 dB (horse 3), a maximum value of 31.6±5.1 dB (horse 4) and an average (all horses) of 23.2±3.8 dB. At 868 MHz, the body loss varied between 24.1±4.8 dB for horse 2 and 36.8±5.6 dB for horse 4, with an average of 31.0±4.7 dB. Just like for cows, higher body loss values were obtained at 1400 MHz with an average of 44.4±3.2 dB. The body loss for horses was lower than for cows for all frequencies. This could be explained by the difference in the depth of the antenna in the body. The antenna was placed in the rumen for cows (a depth of 25 cm) while it was placed close to the stomach for horses (a depth of 20 cm). In addition, the body structure of both animals is different which may lead to different body loss values.

In the previous study [28], the S_{11} calculated by simulation (electromagnetic solver) was used for the body loss calculations. However, the measured S_{11} was used in the current study. The S_{11} when the antenna is implanted in the animal is different than the simulated one and this was not taken in consideration in [28], [40]. This is an important limitation of the previous study. In addition, the experimental setup was refined in the current study. Only the experimental animal was kept in the measurement area, ensuring that no other animals are influencing the received signal. This factor is important as it can change the obtained path loss values due to the fading of the signal. This justifies the difference in the results between the previous and this work.

The antennas used in this study are designed primarily for humans. Future will investigate the design of antennas for animals. The number of subjects is another limitation of the study. Future work will investigate a large number of animals.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2021.3060501, IEEE Transactions on Antennas and Propagation

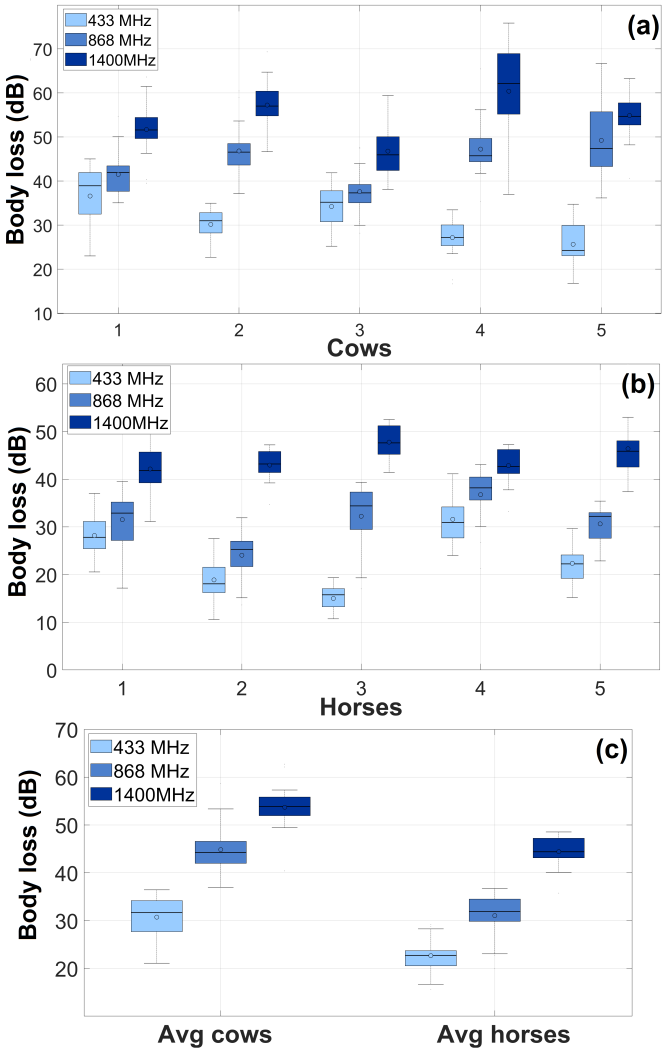

Fig. 4. Boxplot of the in-to-out body loss for each individual (a) cow and (b) horse as well as (c) the average along all cows and horses.

IV. Conclusion

The in-to-out-body body loss was experimentally characterized for five cows and five horses at 433, 868, and 1400 MHz. The body loss for cows was 30.8±4.1 dB, 44.5±4.8 dB, 54.2±4.7 dB for 433, 868, and 1400 MHz, respectively (mean±standard deviation over 5 subjects). For horses, the body loss was 23.2±3.8 dB, 31.0±4.7 dB, 44.4±3.2 dB for 433, 868, and 1400 MHz, respectively.

This characterization can be used to determine the wireless range of WBANs and to design optimal network topologies with the associated network costs for large-scale in-body animal monitoring systems. Based on the established results, further experiments could be designed and conducted to quantify the effect of surrounding tissue properties and environment (none line-of-sight) on the propagation loss. Future work also includes characterization of propagation losses in other large animal species such as goat or sheep. In addition, an optimal transmitter antenna type and parameters for a given animal could be studied and identified.

Acknowledgment

The authors would like to thank Leen Vandaele and Sara Van Lembergen for their help during the measurements. Said Benaissa is a Post-Doctoral Fellow of the FWO-V (Research foundation Flanders, Belgium).

References

[1] J. Ahmad and F. Zafar, “Review of Body Area Network Technology and Wireless Medical Monitoring,” *Int. J. Inf. Commun. Technol. Res.*, vol. 2, no. 2, pp. 186–188, Feb. 2012.

[2] L. Nöbrega, P. Gonalves, P. Pedreiras, and J. Pereira, “An IoT-based solution for intelligent farming,” *Sensors*, vol. 19, no. 3, pp. 603–627, Jan. 2019.

[3] S. Neethirajan, S. K. Tuteja, S. T. Huang, and D. Kelton, “Recent advancement in biosensors technology for animal and livestock health management,” *Biosens. Bioelectron.*, vol. 98, pp. 398–407, Jul. 2017.

[4] N. Zehner, J. J. Niederhauser, M. Schick, and C. Umstatter, “Development and validation of a predictive model for calving time based on sensor measurements of ingestive behavior in dairy cows,” *Comput. Electron. Agric.*, vol. 161, pp. 62–71, Jun. 2019.

[5] V. Ouellet, E. Vasseur, W. Heuwieser, O. Burfeind, X. Maldague, and É. Charbonneau, “Evaluation of calving indicators measured by automated monitoring devices to predict the onset of calving in Holstein dairy cows,” *J. Dairy Sci.*, vol. 99, no. 2, pp. 1539–1548, Dec. 2016.

[6] R. Jonsson, M. Blanke, N. K. Poulsen, F. Caponetti, and S. Hojsgaard, “Oestrus detection in dairy cows from activity and lying data using on-line individual models,” *Comput. Electron. Agric.*, vol. 76, no.1, pp. 6–15, Mar. 2011.

[7] L. M. Andersson, H. Okada, R. Miura, Y. Zhang, K. Yoshioka, H. Aso, and T. Itoh, “Wearable wireless estrus detection sensor for cows, *Comput. Electron. Agric.*, vol. 127, pp. 101–108, Sept. 2016.

[8] H. Hogeveen, C. Kamphuis, W. Steeneveld, and H. Mollenhorst, “Sensors and clinical mastitis-the quest for the perfect alert,” *Sensors*, vol. 10, pp. 7991–8009, Aug. 2010.

[9] A. Van Nuffel, I. Zwertvaegher, L. Pluym, S. Van Weyenberg, V. M. Thorup, M. Pastell, B. Sonck, and W. Saeys, “Lameness detection in dairy cows: Part 1. How to distinguish between non-lame and lame cows based on differences in locomotion or behavior,” *Animals*, vol. 5, no. 3, pp. 838–860, Aug. 2015.

[10] A. Eerdekens, M. Deruyck, L. Martens, J. Fontaine, L. Martens, E. De Poorter, and W. Joseph, “Automatic equine activity detection by convolutional neural networks using accelerometer data,” *Comput. Electron. Agric.*, vol. 168, Jan. 2020.

[11] I. E. Radoi, J. Mann, and D. K. Arvind, “Tracking and monitoring horses in the wild using wireless sensor networks,” *in Proc. 11th Int. Conf. on Wireless and Mobile Computing, Networking and Communications (WiMob2015)*, Abu Dhabi, United Arab Emirates, pp. 732–739, 2015.

[12] S. Bosch, F. Serra Bragança, M. Marin-Perianu, R. Marin-Perianu, B. J. van der Zwaag, J. Voskamp, W. Back, R. van Weeren, and P. Havinga, “Equimoves: A wireless networked inertial measurement system for objective examination of horse gait,” *Sensors*, vol. 18, pp. 1–35, Mar. 2018.

[13] J. F. Marshall, D. G. Lund, and L. C. Voute, “Use of a wireless, inertial sensor-based system to objectively evaluate flexion tests in the horse,” *Equine Vet. J.*, vol. 43, pp. 8–11, Dec. 2012.

[14] R. Antanaitis, V. Zilaitis, V. Juozaitiene, and R. Stoskus, “Usefulness of acidity and temperature of the rumen and abomasum in diagnosing SARA in dairy cows after calving,” *Pol. J. Vet. Sci.*, vol. 19, no. 3, pp. 553–558, Sept. 2016.

[15] I. Eihvalde, D. Kairisa, and I. Sematovica, “Long-term continuous monitoring of ruminal pH and temperature for dairy cows with indwelling and wireless data transmitting unit,” *in Proc. 15th International Conference on Engineering for Rural Development*, Jelgava, Latvia, pp. 726–731, 2016.

[16] S. Benaissa, D. Plets, E. Tanghe, G. Vermeeren, L. Martens, B. Sonck, F. Tuyttens, J. Hoebeke, N. Stevens, and W. Joseph, “Characterization of the on-body path loss at 2.45 GHz and energy efficient WBAN design for dairy cows,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4848–4858, Nov. 2016.

[17] S. Benaissa, D. Plets, E. Tanghe, L. Verloock, L. Martens, J. Hoebeke, B. Sonck, F. Tuyttens, L. Vandaele, N. Stevens, and W. Joseph, “Experimental characterisation of the off-body wireless channel at 2.4 GHz for dairy cows in barns and pastures,” *Comput. Electron. Agric.* vol. 127, pp. 593–605, Sept. 2016.

[18] S. Benaissa, D. Plets, E. Tanghe, J. Trogh, L. Martens, L. Vandaele, L. Verloock, F. Tuyttens, B. Sonck, and W. Joseph, "Internet of animals: characterisation of LoRa sub-GHz off-body wireless channel in dairy barns," *Electron. Lett.*, vol. 53, pp. 1281–1283, Sept. 2017.

[19] P. A. Floor et al., "In-Body to On-Body Ultrawideband Propagation Model Derived From Measurements in Living Animals," *IEEE Journal of Biomedical and Health Informatics*, vol. 19, no. 3, pp. 938–948, May 2015.

[20] S. Perez-Simbor, C. Andreu, C. Garcia-Pardo, M. Frasson and N. Cardona, "UWB Path Loss Models for Ingestible Devices," *IEEE Trans. Antennas Propag.*, vol. 67, no. 8, pp. 5025–5034, Aug. 2019.

[21] P. Bose, A. Khaleghi and I. Balasingham, "In-Body and Off-Body Channel Modeling for Future Leadless Cardiac Pacemakers Based on Phantom and Animal Experiments," *IEEE Antenn. Wireless Propag. Lett.*, vol. 17, no. 12, pp. 2484–2488, Dec. 2018.

[22] F. Merli et al., "Example of Data Telemetry for Biomedical Applications: An In Vivo Experiment," *IEEE Antenn. Wireless Propag. Lett.*, vol. 11, pp. 1650–1654, 2012.

[23] T. Karacolak, R. Cooper, J. Butler, S. Fisher and E. Topsakal, "In Vivo Verification of Implantable Antennas Using Rats as Model Animals," *IEEE Antenn. Wireless Propag. Lett.*, vol. 9, pp. 334–337, 2010.

[24] D. Nikolayev, M. Zhadobov, P. Karban, and R. Sauleau, "Electromagnetic Radiation Efficiency of Body-Implanted Devices," *Phys. Rev. Appl.*, vol. 9, iss. 2, pp. 024–033, Feb. 2018.

[25] A. Lavric and V. Popa, "Internet of Things and LoRa Low-Power Wide-Area Networks: A survey," in *Proc. International Symposium on Signals, Circuits and Systems*,Iasi, Romania, pp. 1–5, Jul. 2017.

[26] A. Lavric, A. I. Petrariu and V. Popa, "SigFox Communication Protocol: The New Era of IoT?," in *Proc. International Conference on Sensing and Instrumentation in IoT Era*, Lisbon, Portugal, pp. 1–4, Aug. 2019.

[27] J. Ung and T. Karacolak, "A Wideband Implantable Antenna for Continuous Health Monitoring in the MedRadio and ISM Bands," *IEEE Antenn. Wireless Propag. Lett.*, vol. 11, pp. 1642–1645, 2012.

[28] S. Benaissa, D. Plets, D. Nikolayev, M. Deruyck, L. Verloock, G. Vermeeren, L. Martens, E. De Poorter, F. A. M. Tuyttens, B. Sonck, and W. Joseph, "Experimental characterisation of in-to-out-body path loss at 433 MHz in dairy cows," *Electron. Lett.*, Vo.55, no. 7, pp. 422–424, Apr. 2019.

[29] S. L. Laflin and D. P. Gnad, "Rumen Cannulation: Procedure and Use of a Cannulated Bovine," Vet. Clin. North Am. *Food Anim. Pract.*, vol. 24, no. 2, pp. 335-340, Jul. 2008.

[30] D. Nikolayev, W. Joseph, A. Skrivervik, M. Zhadobov, L. Martens, and R. Sauleau, "Dielectric-loaded conformal microstrip antennas for versatile in-body applications," *IEEE Antenn. Wireless Propag. Lett.*, vol. 18, no. 12, pp. 2686–2690, Dec. 2019.

[31] D. Nikolayev, M. Zhadobov, L. Le Coq, P. Karban, and R. Sauleau, "Robust ultra-miniature capsule antenna for ingestible and implantable applications," *IEEE Trans. Antennas Propag.*, vol. 65, no. 11, pp. 6107–6119, Nov. 2017.

[32] S. Gabriel, R. W. Lau, and C. Gabriel, "The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz," *Phys. Med. Biol.*, vol. 41, pp. 2251–2269, Nov. 1996.

[33] Computer simulation technology AG, *CST Microwave Studio*, Feb. 20, 2018. [Online]. Available: http://www.cst.com

[34] D. Nikolayev, M. Zhadobov, P. Karban, and R. Sauleau, "434 MHz ISM band antenna for in-body biotelemetry capsules," in *Proc. 11th Eur. Conf. on Antennas and Propagation (EuCAP 2017)*, Paris, France, pp. 1035–1038, 2017.

[35] ETS-Lindgren, 3164-06 Quad-Ridged Horn, Feb. 20, 2018. [Online]. Available: http://www.ets-lindgren.com/3164-06.

[36] D. Nikolayev, W. Joseph, M. Zhadobov, R. Sauleau, and L. Martens, "Optimal radiation of body-implanted capsules," *Phys. Rev. Lett.*, vol. 122, no. 10, pp. 108–101, Mar. 2019.

[37] D. Nikolayev, M. Zhadobov, and R. Sauleau, "Impact of tissue electromagnetic properties on radiation performance of in-body antennas," *IEEE Antenn. Wireless Propag. Lett.*, vol. 17, no. 8, pp. 1440–1444, Aug. 2018.

[38] E. Reusens, W. Joseph, B. Latre, B. Braem, G. Vermeeren, E. Tanghe, L. Martens, I. Moerman, and C. Blondia, "Characterization of on-Body communication channel and energy efficient topology design for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, no. 3, pp. 933–945, Nov. 2009.

[39] P. S. Hall, Y. Hao, Y. I. Nechayev, A. Alomalny, C. C. Constantinou, C. Parini, M. R. Kamarudin, T. Z. Salim, D. T. M. Hee, R. Dubrovka, A. S. Owadally, W. Song, A. Serra, P. Nepa, M. Gallo, and M. Bozzetti, "Antennas and propagation for on-body communication systems," *IEEE Antenn. Propag. Mag.*, vol. 49, no. 3, pp. 41–58, Jun. 2007.

[40] S. Benaissa, L. Verloock, D. Nikolayev, M. Deruyck, G. Vermeeren, L. Martens, F. Tuyttens, B. Sonck, D. Plets and W. Joseph, "Joint antenna–channel modelling for in-to-out-body propagation of dairy cows at 868 MHz," *in Proc. 14th Eur. Conf. on Antennas and Propagation (EuCAP 2020)*, Copenhagen, Denmark, pp. 1–4, Mar. 2020

[41] M. Grimm and D. Manteuffel, "Electromagnetic wave propagation on human trunk models excited by half-wavelength dipoles," *in Proc. Loughborough Antennas and Propagation Conference (LAPC2010)*, Loughborough, United Kingdom, pp. 493–496, Nov. 2010.

[42] D. Kurup, W. Joseph, E. Tanghe, G. Vermeeren, and L. Martens, "Extraction of antenna gain from path loss model for in-Body Communication," *Electron. Lett.*, vol. 47, no.23, pp. 1262–1263, Nov. 2011.

[43] D. Kurup, G. Vermeeren,E. Tanghe, W. Joseph, and L. Martens, "In-to-Out Body Antenna Independent Path Loss Model for Multilayered Tissues and Heterogeneous Medium," *Sensors*, vol. 15, no.1, pp. 408–421, Jan. 2015.

[44] J. Naganawa, M. Kim, T. Aoyagi, and J. Takada, "FDTD-based antenna de-embedding in WBAN on-body channel modeling," in *in Proc. 31th URSI General Assembly and Scientific Symposium, URSI GASS 2014*, Beijing, China, 2014.