Experimental Characterization of In-to-Out-Body Path Loss at 433 MHz in Dairy Cows

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In this letter, for the first time, the in-to-out-body path loss between an antenna placed inside the cows' rumen and a distant gateway was characterized at 433 MHz. Measurements were conducted on seven different fistulated cows using a signal generator and a spectrum analyser. A subsequent measurement of the antenna in free space was used to quantify the path loss increase due to the cow body. Results have shown an increase of the path loss by 45.5 dB on average (all cows), with a variation between 39.7 dB and 51.1 dB. In addition, the measured path loss values as a function of the transmitter-receiver distance in a dairy barn were well fitted by a log-normal path loss model. The obtained models were used to calculate the range of a LoRa (Long range) based network. Ranges up to 100 meters were obtained depending on the used transmit power and bit rate.

Introduction: The size of dairy farms and the number of animals per stockperson are increasing. Within larger herds, timely detecting health problems of individual cows becomes a challenging and costly task. Monitoring health indicators (e.g., ruminal temperature and pH) in real time using sensors enables large dairy farms to optimize their profits as well as increase their cow welfare. Ruminal temperature and pH are important parameters to assess the nutritional and health status of dairy cows and to predict anomalies (e.g., metabolic disorders after calving) [1]. However, these parameters can be measured only by using in-body sensors. In practice, for a real-time data collection, the in-body sensor would wirelessly transmit the measured data to a nearby gateway. Therefore, the reliability of the in-to-out-body wireless communication is crucial for collecting such data.

Wireless Body Area Networks (WBANs) and Internet-of-Things (IoT) can be effectively used for health tracking of dairy cows to facilitate herd management and enhance cow welfare (IoA, Internet-of-Animals) [2]. Moreover, recent advances in low-power wireless communication technologies (e.g., Long Range (LoRa), Sigfox) working at 433 MHz allow long-range wireless communications and are scalable towards a large number of devices. Several studies have investigated the on- and off-body wireless communication for WBANs and IoT applications for animals [2, 3]. However, to the best of authors' knowledge, the in-to-out-body wireless link has not been investigated yet for dairy cows. The aim of this study is to characterize the path loss between a transmitter placed inside a cow's rumen and a distant gateway at 433 MHz for different dairy cows. Accurate link budget calculations will safeguard the reliability of the in-body-based monitoring system for dairy cattle.

Path loss measurements: Measurements were conducted in a research barn at the Flanders Research Institute for Agricultural, Fisheries and Food (ILVO) in Melle, Belgium. In-to-out-body measurements were performed in a large area of about 6 m × 18 m. Seven different fistulated dairy cows were used for the measurements. Fistulated cows are cows that have been surgically fitted with a cannula. A cannula acts as a porthole-like device that allows access to the rumen of a cow, to perform research and analysis of the digestive system. The cows were tied at a fixed position as shown in Fig. 1-a.

The setup of the path loss measurements is shown in Fig. 1-a. The transmitter part was composed of a transmitting antenna (TX) and a signal generator. As the TX, the capsule antenna (Fig. 1-b, height 17 mm, diameter 7 mm) described in [4] was used. The antenna has high robustness and efficiency (compared with counterparts) and it is suitable for a wide range of in-body applications. Although it is designed for humans, the antenna may also be considered for animal biotelemetry due to its high robustness [4]. The TX antenna was placed in the bottom of the rumen of the fistulated cow (20 cm to the abdominal wall and 80 cm to the cow's back) and connected to an amplifier and a signal generator. The Rohde & Schwarz SMB100A (100 kHz–12.75 GHz) signal generator was used to inject a continuous wave signal at 433 MHz. The power at the output of the amplifier (injected to the antenna) was 32 dBm.

The receiver part (RX) was composed of the EMF probe (Rohde & Schwarz TS-EMF, Italy) connected to a spectrum analyser and a laptop to store the data. The EMF probe was used to measure the three components of the received electric field (no influence of the antenna orientation). The measurements were carried out for different TX–RX separations (1 to 20 m) behind the cow. At each measurement location, 300 samples were recorded. The mean value of the samples was considered as a received power for the corresponding TX–RX separation. The measurements were performed also without cow. In this case, the TX antenna was mounted in free space at a height of 0.8 m (i.e., the distance from the bottom of the rumen to the ground). The measurements without cow were carried out to quantify the increase of path loss due to the cow's body.

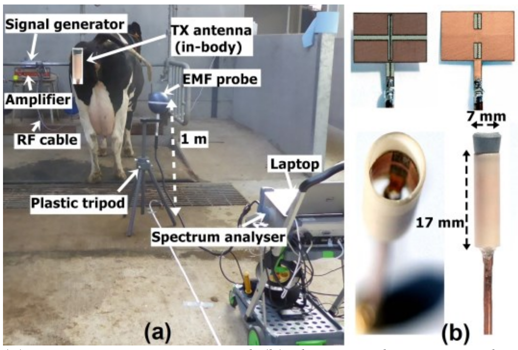

Fig. 1 *(a) Measurement setup and (b) the capsule antenna designed for ingestible and implantable applications* [4].

Path loss modelling: As presented in [2], the path loss (PL) for WBANs is calculated as follows (i.e., antenna de-embedded path loss):

$$PL = P_{TX} + G_{TX\_b} - L_{TX} + G_{RX} - L_{RX} - P_{RX} \quad (1)$$

where P_{TX} is the transmitter power (dBm), G_{TX_b} is the gain of the TX antenna inside the cow body, L_{TX} transmitter cable losses (dB), G_{RX} receiver antenna gain in free space (dBi), L_{RX} the receiver cable losses (dB), and P_{RX} is the received power in dBm.

For anatomical tissue models, gain is not isotropic but varies with the direction. The maximum realized gain is –26.3 dBi taking into account the losses of the body. In free space, the gain of the capsule antenna was calculated using the electromagnetic solver Sim4Life [5] based on the finite-difference time domain (FDTD) computation method. The conformal model of the antenna as described in [4] was considered. In this case, a maximum realized gain of –53.9 dBi was obtained. The low realized gain is due to the strong mismatch in air (|S11| ≈ –0.9 dB) since the antenna was specifically designed for in-body applications and relies on dielectric loading by tissues to achieve higher efficiencies [6]. The values of the realized gain in air and in-body were used to calculate the de-embedded antenna path loss (equation 1).

Finally, to model the path loss as a function of the TX–RX separation, a log-distance path loss model was used. The path loss can be modelled as a linear function of the logarithmic distance between the transmitter and receiver, as explained in [6]:

$$PL(d) = PL(d_0) + 10n\,log\left(\frac{d}{d_0}\right) + X_\sigma \quad (2)$$

with $PL(d_0)$ is the path loss at a reference distance $d_0 = 1$ m, n the path loss exponent, d the separation distance between TX and RX (m), and X_σ is a zero-mean Gaussian distributed variable (dB) with a standard deviation σ (dB).

Results: Fig. 2-a shows the increase of the path loss [PL difference, $PL(\text{cow}) - PL(\text{without cow})$] due to the cow body for each individual cow as well as the average over all cows. The mean value of the path loss difference (over all distances) varied between 39.7 dB (cow 4) and 51.5 dB (cow 7) with an average (all cows) of 45.5 dB (Table 1). This variation was expected since the cows have different sizes and the quantity of feed in their rumen differs. The standard deviations varied between 5 to 6 dB for all cows. We note that these values quantify the real loss in power due to cow body without antenna loss (in-to-out-body antenna de-embedded path loss). This additional path loss due to the cow's body is relevant in the link budget calculation (see Application).

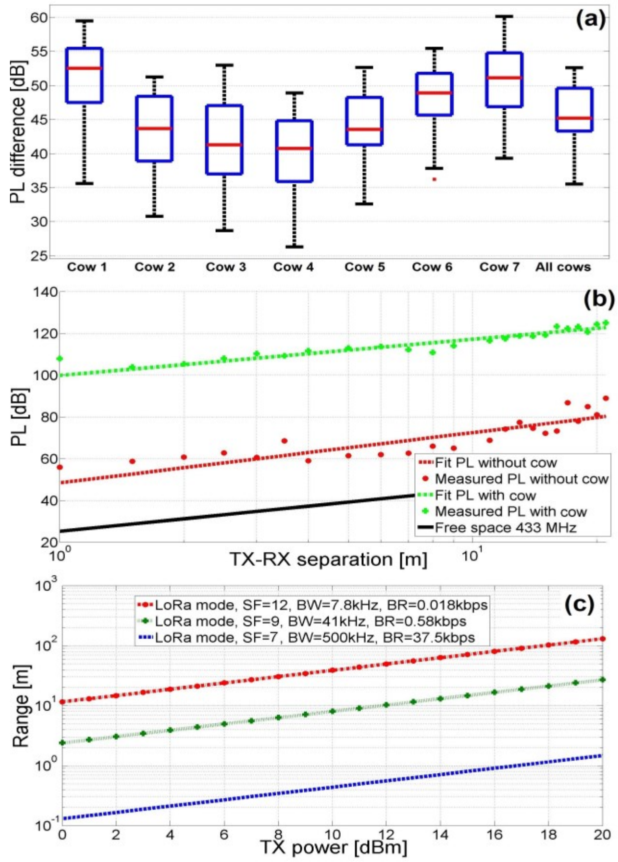

Fig. 2. (a) *Boxplot of the path loss increase due to the cow body for each individual cow and the average along all cows, (b) the path loss models for the two scenarios (with and without cow) and (c) the calculated network ranges for minimum, typical, and maximum bit rates (0.018, 0.58, 37.5 kbps), SF: spreading factor, BW: bandwidth, BR: bit rate*.

Table 1: The mean, the median, and the standard deviation (SD) of the path loss difference for each individual cow and for all cows (Avg).

Cows	1	2	3	4	5	6	7	Avg
Mean	50.6	43.3	41.2	39.7	44.2	48.3	51.1	45.5
Median	52.6	43.7	41.3	40.8	43.6	48.9	51.2	45.2
SD	6.3	5.9	6.3	6.4	5.4	5.1	5.5	5.1

The obtained path loss models in the barn are shown in Fig. 2-b. As expected, the path loss was higher when the TX antenna was in the rumen of the cow compared to the path loss without cow. The increase in path loss as a function of the TX–RX separation is quantified by looking into the parameters of path loss models listed in Table 2. The path loss $PL(d_0)$ at reference distance (1 m) shifted from 48 dB for path loss without cow to 98 dB when the TX was in the cow. The path loss exponent was nearly the same for both scenarios ($n \approx 2$), due to the open area in the barn. Standard deviations (σ) between 2 and 4 dB were obtained for all models, indicating a relatively low shadow fading effect. Coefficients of determination R^2 of 0.76 and 0.93 were obtained, meaning that the log-normal path loss model fits the measured data.

Table 2: Parameters of the path loss models ($d_0 = 1\ m$)

	$PL(d_0)\ (dB)$	$n(-)$	$\sigma(dB)$	$R^2(-)$
PL without cows	48.3	2.1	4.85	0.77
PL with cows	98.5	1.9	1.80	0.93

Application: In this Section, LoRa technology (Long Range) is proposed for in-body data collection for dairy cows. A primary step of network planning is to calculate the network range. Table 3 lists the parameters used for the range calculation. The in-to-out-body path loss model for cows was used. The minimum and the maximum bit rates (0.018 and 37.5 kbps) as well as a typical bit rate (0.58 kbps) were investigated. For each bit rate, the corresponding receiver sensitivity was used (Semtech SX1276 [7]). The other parameters are listed in Table 3. The details of the range calculation are given in [8].

Table 3: Parameter values used to calculate the network range.

Parameters			Unit
In-to-out–body channel model	d_0	1	m
	$PL(d_0)$	98	dB
	n	1.9	[–]
	Ms	3	dB
	Mf	6	dB
Bit rate		[0.018, 0.58, 37.5]	kbps
Sensitivity		[–148, –135, –111]	dBm

Fig. 2-c shows the obtained ranges (m) as a function of the TX power (dBm). Here, a typical transmit power between 0 and 20 dBm is used. With a transmit power of 10 dBm, the ranges are 0.4 m, 8.1 m, and 38.8 for 0.018, 0.58, 37.5 kbps, respectively. This reflects the high attenuation of the signal due to the cow body. When the maximum transmit power of a LoRa transmitter is used (20 dBm), the range reaches 100 m for the minimum bit rate, while it is limited to 11 m when the maximum bit rate is used. Therefore, the range could be extended by using a lower bit rate with a higher transmit power, although this would limit the battery lifetime as well as the amount of the collected data. As a solution, a relay node could be attached to the collar of the cow to forward the received data from the in-body sensor to a nearby gateway as proposed in [2].

Conclusion: The in-to-out-body path loss in dairy cows was characterised for the first time at 433 MHz. Based on the obtained results for seven cows, the path loss increased on average by 45.5 dB, with a standard deviation of 5.1 dB. The path loss as a function of TX–RX distance was well fitted by a log-normal model. The obtained models were used to calculate the range of a LoRa based network. Ranges up to 100 meters were obtained depending on the used transmit power and bit rate.

Acknowledgments: This work was supported by the EOS project MULti-Service WIreless NETwork (MUSE-WINET). Margot Deruyck is a Post-Doctoral Fellow of the FWO-V (Research foundation Flanders, Belgium). The authors would like to thank Leen Vandaele and Sara Van Lembergen for their help during the measurements.

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