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Adaption and assessment of a UHF-RFID system for livestock management

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For a successful technology, reality must take precedence over public relations, for nature cannot be fooled.

Richard Feynman

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GENERAL INTRODUCTION

The digitalisation of crop and livestock farming processes has been discussed intensively for the last two to three years. Under this term, many different developments in automation, data collection and services, as well as the connection of different stakeholders in agricultural supply chains are subsumed (Kunisch, 2016). Closely related to the process of digitalisation is the idea of the Internet of Things, which is a concept of "the pervasive presence around us of a variety of 'things' or 'objects', such as RFID, sensors, actuators, mobile phones, which, through unique addressing schemes, are able to interact with each other and cooperate with their neighboring 'smart' components to reach common goals" (Giusto et al., 2010).

One of the central technologies and driver of a things-oriented perspective of this concept is radio-frequency identification (RFID) (Atzori et al., 2010). Radio-frequency identification uses electromagnetic waves for data exchange between transponders (so-called tags), which carry an unique identification number, and readers, which are connected to databases and information systems (Roberts, 2006). Items labelled with an RFID tag communicate virtually with each other and with the operator of the system by transmitting information about their location and, in some cases, additional status data when they are registered by a specific reader in a known location. Thus, RFID is the starting point of an Internet of Things as a network of items sharing their information with everyone having access to this information system (Atzori et al., 2010). Through automatic identification, RFID also minimises the gap between object and information layer in production, trade or control processes (Kern, 2007). In this way, the expense for data collection, the occurrence of identification and documentation errors, and the effort spent on controls can be reduced strongly.

The sharing of information between all actors in a supply chain and, even more, the assurance of traceability from suppliers to producers, then to processors and, finally, consumers are key issues, especially in food production. The benefits of animal traceability in livestock farming are widely acknowledged for the control and tracking of disease outbreaks (Caporale et al., 2001). Furthermore, information on production numbers, product quality and availability is valuable for all members of the supply chain to optimise production and marketing plans. A gapless traceability is essential and also allows for higher profitability for the marketing of products with guaranteed proof of origin (Dickinson and Bailey, 2005). These circumstances support the use of RFID systems in livestock and food production and will probably cause an increased usage in the future. However, when the electronic identification of animals incorporating RFID is used, there is an added value besides efficient traceability that can be exploited, for example, in precision livestock farming (PLF) systems.

The general concept of PLF is based on the principles of process engineering and control theory. Animal husbandry systems are considered as complex and parallel processes with various input and output variables that are measured with different sensors and then processed in a control system. The overall objective of this approach is the optimisation of husbandry systems in terms of animal welfare and health, environmental impact and productivity (Wathes et al., 2008). Using RFID could be a central part of the sensor network in these systems, not only to identify the individual animals, but furthermore as a tool for behaviour monitoring through the registration of animals at certain points in their environment (e.g. the barn). This means that animals would partly control their environment themselves by delivering input to control mechanisms, for example, for the feeding or ventilation system (Wathes et al., 2008). Together with the concept of delivering information about the production process along the supply chain and for herd management on the farm, RFID would, thus, integrate PLF with the idea of the Internet of Things.

Radio-frequency identification has been used in animal husbandry for about 40 years. Agricultural engineers were among the first adaptors of RFID for applications in animal husbandry in the 1970s when animal traceability was not prominent and RFID technology was only in the transition stage from research to application. A conference was held in The Netherlands in 1976 where research groups from the USA, the UK, The Netherlands, and Germany presented their first developments for the identification of cows (Instituut voor Mechanisatie, Arbeid en Gebouwen, 1976; Rossing, 1999). These first systems were designed mainly for the individual feeding of concentrates and for identification of the cows in the milking parlour to track individual milk production (Duinker, 1976). Both applications were not only conceived to improve the efficiency of milk production and increase the milk yield, but the researchers were also already working on integrating the identification technology into herd management software (Duinker, 1976). A clear additional benefit of electronic animal identification with a perspective towards today’s research into intelligent digital networks and systems is already evident here.

Some of the first cow transponders were already working passively without external power supply, which is still an enormous advantage today regarding durability compared to battery-supported technologies. The transponders were mainly attached to collars, but experiments were also made with boluses for insertion into the rumen and with subdermal implants. The successful development of smaller transponders at low cost for use in ear tags, which are the devices most commonly used for visual and electronic animal identification nowadays, and small subdermal implants was enabled by use of integrated circuit technology in the 1980s (Rossing, 1999). This was followed by the fast growth of the market for electronic animal identification. The ISO standards 11784 and 11785, which define the code structure and the technical concept of animal identification with passive RFID, were established in 1996 (Schwalm and Georg, 2011). These technical standards specify an operating frequency of 134.2 kHz for the animal RFID systems. This frequency is categorised as low-frequency (LF) RFID. The LF-RFID technology has spread to many applications, from driving races for the sorting of sheep, through electronic sow-feeding stations to the identification of cows at milking robots and sorting gates. It is also basis of worldwide regulations for mandatory electronic animal identification.

With the operation frequency of an RFID system also functional characteristics are connected. The data exchange rate decreases with lower operation frequency (Kern, 2007). Thus, the registration of a single transponder takes a relatively long time in LF-RFID systems, consequently, anti-collision algorithms are only inefficiently applicable (Burose et al., 2010). An alternative way to obtain simultaneous identification of multiple transponders with this technology is by using multiple readers or reader antennas and multiplexers, thus, a single animal can be identified with each antenna (Brown-Brandl and Eigenberg, 2011; Rößler et al., 2011). This naturally causes increased hardware expenses compared to systems using anti-collision algorithms. Furthermore, the read range of an LF-RFID system is limited to approximately 0.2 to 1.0 m, depending on the reader antenna and transponder used (Ruiz-Garcia and Lunadei, 2011).

These characteristics become limiting factors when thinking about new applications of RFID technology regarding monitoring the behaviour of animals. Animals are kept in groups in most husbandry systems, so that simultaneous identification is necessary in many cases. Consequently, researchers carried out experiments with high-frequency (HF, 13,52 MHz) RFID systems, which allow for the use of anti-collision algorithms. Thurner et al. (2010), for example, detected laying hens at a pop-hole leading to an open-air area. Due to the possibility of detecting several hens at a time, the pop-holes could be enlarged significantly, compared to a previous version with LF-RFID, to minimise the influence of the observation technology on the behaviour of the hens (Thurner et al., 2010). Reiners et al. (2009) and Maselyne et al. (2014; 2016a) measured the feeding and drinking behaviour of weaned piglets and growing-finishing pigs at a round trough and nipple drinkers with HF-RFID. The results of these studies are very promising, however, the read range of HF-RFID systems is approximately the same as LF-RFID, because both technologies work with inductive coupling in the magnetic near-field of the reader antenna. Therefore, the suitability of HF-RFID for continuous observation of the whole living environment of the animals is limited.

Ultra-high frequency (UHF, 860 – 960 MHz) RFID systems offer a high read range of typically more than 3 m, depending on the application and the hardware used, and also a very high speed of communication, theoretically facilitating the detection of several hundred transponders per second (Ruiz-Garcia and Lunadei, 2011; Namboodiri et al., 2012). Nevertheless, the advantages of UHF-RFID cannot often be utilised completely because of the negative influence of body tissue near the transponders (Lorenzo et al., 2011), but recent advances in the technology support a positive perspective of an introduction of UHF-RFID to livestock farming (Umstatter et al., 2014).

The first UHF-RFID products, mainly ear tags for cattle and some for pigs and sheep, have been commercially available for a few years. Several scientific and industrial projects have also tested UHF-RFID equipment for use with cattle, pigs, sheep and deer (Moxey, 2011; Stekeler et al., 2011; Baadsgaard, 2012; Hogewerf et al., 2013; Pugh, 2013; Rosei Project Group, 2013). The focus was on traceability and the simultaneous detection of animals in all these projects. Behaviour monitoring with UHF-RFID has not yet been tested. The results of the experiments carried out also showed that further research is necessary to achieve reliable identification of UHF transponder ear tags. Furthermore, most of the equipment, transponder ear tags, readers and antennas were not perfectly adapted to the harsh conditions in livestock farming.

Against this background, a joint research project was started in 2012 with the aim of developing UHF-RFID readers, antennas and passive transponder ear tags especially for use in cattle and pigs (Federal Office for Agriculture and Food, 2012). The scientific focus of this project was the development of methods for the testing and assessment of the new technical components and the test of practical applications. This thesis presents a part of the research carried out within the frame of the project. Dynamic tests, simultaneous identification of cattle and pigs, and a cost-benefit analysis of the UHF system for behaviour monitoring and management were part of another work (Hammer et al., 2015; Hammer et al., 2016a; Hammer et al., 2016b). This study concentrates on the methodical aspects of static tests of UHF transponder ear tags and the practical application of the technology in behaviour monitoring.

The overall objective of this thesis was to determine characteristics of UHF-RFID transponder ear tags that are beneficial for the adaption of this technology for use in livestock management and the assessment of the general suitability of UHF-RFID for behaviour monitoring of farm animals.

A method for static tests of UHF transponder ear tags is presented in **Chapter 1**. These tests facilitated the evaluation of the reading area of the ear tags by measurements of read range and received signal strength indicator (RSSI) in different orientations to the reader. In **Chapter 2,** these tests were complemented by measurements of the influence of ear tissue on the performance of the transponder ear tags. A practical application of these ear tags and of a complete UHF-RFID system is shown in **Chapter 3**. Here, the registration of trough visits of growing-finishing pigs was examined as a first approach to monitor animal behaviour with a UHF-RFID system.

CHAPTER 1

DEVELOPMENT, FUNCTION AND TEST OF A STATIC TEST BENCH FOR UHF-RFID EAR TAGS

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Development, function and test of a static test bench for UHF-RFID ear tags

Felix Adrion, Nora Hammer, Benjamin Rößler, Dagmar Jezierny, Anita Kapun, Eva Gallmann

Ultra-high-frequency radio frequency identification systems (UHF-RFID systems) offer multiple application possibilities for animal identification. In a present joint project, UHF transponder ear tags and readers are currently being developed especially for use with cattle and pigs. An automatic test bench was developed for measuring the detection area and signal strength of various transponders, the aim being to enable with this test bench comparison of different types of UHF-transponder ear tags in different orientations to reader antennas. Described in this paper is the constructional development and functionality of the test bench as well as trials to determine reproducibility, influence of two trial parameters and suitability of the test bench for the required purpose. The results demonstrate that the test bench fulfilled all the stipulated requirements and enabled a preliminary selection of suitable types of UHF ear tags for use in practice.

Key words
Electronic animal identification, UHF RFID, RSSI, test bench, transponder

Electronic animal identification has established its place in modern livestock production. Its use ranges from the mandatory identification of small ruminants for securing traceability (Schwalm and Georg 2011), over utilisation of the identification data for dairy cows and breeding sows in farm management (Ruiz-Garcia and Lunadei 2011, Trevarthen and Michael 2008), to complex data recording on experimental farms (Büttering 2011). In addition to the standard systems applied under ISO 11785, based on low-frequency radio frequency identification (LF-RFID, 134.2 kHz), the application of RFID in the high-frequency range (HF-RFID, 13.56 MHz) (Hessel and Van den Weghe 2013, Leong et al. 2007, Maselyne et al. 2014) and ultra-high-frequency range (UHF-RFID, 860960 MHz) (Hogewerf et al. 2013, Ng et al. 2005, Stekeler et al. 2011, Umstatter et al. 2014) is increasingly tested in research in recent years. One reason for this is that anti-collision methods with LF-RFID can only be applied in a very limited form because of the low data transference rate in this frequency range. Anti-collision systems prevent data collisions that occur when a number of transponders are present at the same time within the antenna field of a reader. For instance, widely applied is the slotted ALOHA procedure whereby transponders are allocated random time windows during which they send their respective data to the reader (Finkenzeller 2012, Namboodiri et al. 2012). The quasi-simultaneous reading of transponders hereby enabled is advantageous, e.g., to the RFID system in the detection of animal groups where individual animal identification is no longer required. Compared with LF-RFID, HF-RFID can enable the practical application of quasi-simultaneous reading through a higher data transmission rate (Burose et al. 2010, Hessel and Van den Weghe 2013, Kern 2007). However, the effective reading distance of both systems is a maximum of approx. 1 to 1.5 m. In the UHF range, alongside the simultaneous reading of transponders, a significantly higher reading range of more than 3 m with passive tran-

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sponders can also be achieved (Ruiz-Garcia and Lunadei 2011). Hereby, a large number of application possibilities for UHF transponders in animal production is produced including simultaneous reading of large animal groups, monitoring feeding behaviour or localising to determine activity behaviour of animals in the group. However, there are also disadvantages with the higher working frequency such as marked absorption by water or body tissue, as well as reflection on electrical conductive surfaces. The latter problem causes fluctuating interference patterns that lead to inhomogeneity within the antenna field. Additionally, materials in the vicinity of the transponder cause a change in impedance (alternating current resistance) of the transponder antenna through their permittivity (permeability for electrical fields) and thus a shifting of the transponder resonance frequency. In most cases, a reduction in resonance frequency is to be expected (Rao et al. 2005). All these factors influence the reading range and identification reliability of UHF transponder ear tags and necessitate appropriate adjustment of transponder antennas for use with animals (European EPC Competence Center (EECC) 2011, Finkenzeller 2012, Kern 2007, Lorenzo et al. 2011, Rao et al. 2005).

For assessing UHF transponders for their reading distance, their sensitivity to being attached to various materials, or to transmitting frequency and further characteristics, standardised measurements are conducted in absorber chambers that guarantee freedom from interference and reproducibility of results. A known test of this type is the "UHF Tag Performance Survey" annually conducted by the European EPC Competence Center (EECC, Neuss, Germany) (European EPC Competence Center (EECC) 2011). A precise description of the measuring approach applied there is given by Derbek et al. (2007). Disadvantages of using this procedure include the high technical input involved and the required testing of individual parameters instead of the entire RFID system. In contrast to this, results are not generalisable in practical trials with the entire system and not reproducible over a longer period because of the changing environment conditions. For these reasons, some authors have taken a middle way and conduct tests of UHF systems in model-type laboratory trials, the set-up of which represents a particular section of application in practice, offering a better reproducibility than in practical trials (Jungk 2010, Mainetti et al. 2013). Jungk (2010) emphasises the absolute necessity of sufficiently repeated measurements for securing accuracy of results against environment influences that occur in a trial environment without surrounding absorbance material. Kern (2007) also presented some possibilities for simple tests for transponders and warned of the danger that these applications did not in every case sufficiently satisfy scientific requirements.

Defining problems and objectives

An innovation project supported by the Federal Ministry for Food and Agriculture (BMEL) currently develops UHF transponder ear tags for identification of cattle and pigs as well as readers for simultaneous reading and locating UHF transponders (Forschungsinformationssystem Agrar/Ernährung 2012). Main target hereby is adapting the RFID system to meet the requirements and conditions in animal farming and the attachment of transponder ear tags to animals. For selection of suitable antenna design and ear tag construction, especially with regard to sufficient reading distance, acceptable directional characteristics, and readability in the vicinity of ear tissue, the function patterns of different transponder types were tested in test bench trials before use with animals. For this, two test benches were designed for testing transponders under dynamic and static conditions. In the dynamic tests, a comparison of transponders under various speeds and in different directions is possible which reflect in model form the application of the system in practical driving trials (Hammer et al. 2015).

Additionally of interest is the size and form of the effective transponder ear tag reading area and signal strength in relationship to various factors. These parameters can be investigated with non-moving (static) transponders.

Presented in this paper will be a static test bench that enables measurement of recognition area and signal strength of UHF transponder ear tags in combination with various reading apparatus and their settings. Main target hereby is comparison of ear tags with different types of UHF transponders. This should enable an overall assessment of transponder types as well as observation of individual orientations of the ear tags to the reader antenna. For the measurements involved, the transponder ear tags must be positioned in various orientations within the field of a reader according to defined matrix dots (Kern 2007). In order to efficiently conduct these time-consuming trials, the test bench was to a large extent automated. Because the test bench was not situated in an interference-free testing environment (absorber chamber), influences from fluctuating reflections and absorption characteristics through changes in the immediate environment could not be ruled out. Because of this, preliminary methodical trials were conducted with the test bench to determine the reproducibility of measurements, the influence of the holders used for the ear tags and the influence of the sequence of the measured coordinates. Subsequently, different types of UHF ear tags to be used in testing the actual application of the test bench were compared. In the following, construction and function of the test bench are explained and test results presented. There then follows an assessment of the suitability of the test bench for the planned measurements on UHF transponder ear tags.

Materials and methods

Construction and function of the test bench

Main components of the test stand are two linear drives crossing at right angles within a 350 cm x 350 cm horizontal work area positioned 34 cm above floor level. These represent the x- and y-axes of the area within which a tracked slide slotted into the x-axis drive line can be moved to every coordinate. Hereby, the y-axis supports the middle of the x-axis (Figure 1). A 125 cm high pillar of extruded polystyrene (XPS, Styrodur®) is fitted onto the slide and serves as holder for the transponder ear tags. Polystyrene was selected as holder material because of its small influence on the reader electromagnetic emissions (relative permittivity $\varepsilon_r = 1.03$) and is also used in standardised transponder tests (Derbek et al. 2007, European EPC Competence Center (EECC) 2011, Webster and Eren 2014). The ear tags can be positioned individually in exchangeable polystyrene foam blocks on the upper end of the pillar in all required orientations to the reader antenna. In the tests, the tags are situated 165 cm above floor level. The reader antennas could also be positioned where required, individually or more than one together, at freely selectable points in various alignments around the test bench. In this way, the antennas can also be positioned at greater distances from the test bench so that measurements can also be made for transponders able to be read at greater distances by readers at their maximum settings. Positioning precision of transponders relative to readers represented around 1 cm under consideration of all error sources, such as, in particular, the play of the parallel tracking of the x-axis, the alignment of the transponder in the holder and the positioning of the reader antenna (Adrion et al. 2014).

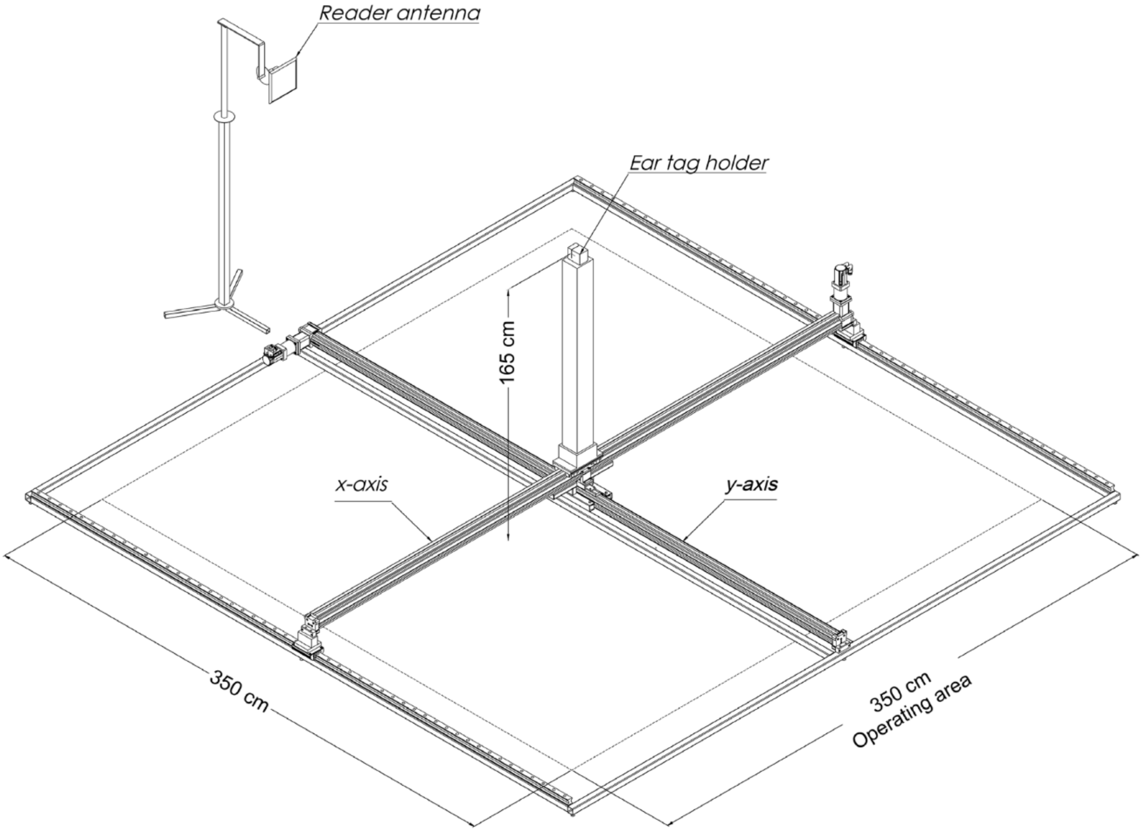

Figure 1: Test bench model diagram

The servomotors of the linear drives and the reader have a central control. The operator can configure the test stand via a LabVIEW® application and call up test results, start tests, and also allow procedure to be followed automatically. The tests were configured beforehand in a central configuration software (Phenobyte GmbH & Co. KG, Ludwigsburg) and stored in a test database. Important parameters such as proven coordinate area, coordinate matrix, transponder number, transponder orientation, reader configuration and antenna alignment are established in this work phase. All readings from each test are entered into the database together with the respective registered coordinates (Adrion et al. 2014).

An individual test run comprises the measurement of a transponder in a particular position with defined reader configuration and position. During a test run, the predetermined coordinate matrix is automatically processed. This can take place either in random sequence or in rising or falling order of coordinate sequence on both axes. On every coordinate the slide is halted during a procedure and the reader, after a short pause (< 1000 ms), activated for a defined period (100 ms to 65000 ms) and the readings from the transponder during this period registered. The number of readings is mainly dependent on the different settings of the reader, such as the interval after which the so-called "inventoried flag" of the transponder is reset in the anti-collision process. But the transponder energy supply also influences the number of readings per time period. Thus, on the limits of the reading area the number of readings sinks because of the poorer energy supply for the transponder (Adrion et al.

2014). During each reading, the reader measures an indicator for the transponder signal reception strength (Received Signal Strength Indicator, RSSI). The size of this value is reader-specific because the received signal is multiplied by a reader-dependent scaling factor. Physically, the measured value is mainly dependent on the distance d between reader antenna and transponder. Further influences on the measured RSSI are the supply power of the reader antenna P_r, the antenna gain G_r and G_t from reader or transponder, the wavelength λ and the backscatter loss ratio L (Equation 1) (Choi et al. 2009, Finkenzeller 2012). In the following, the RSSI is given dimensionless as power level in decibel milliwatts (dBm). Equation 2 may be used for calculation of the units milliwatt and decibel milliwatt. As well as the given factors, the RSSI course may also be influenced by an environment with reflections through changes of the so-called path loss exponent. With an ideal free space propagation, the path loss exponent has the value 2 with regard to one way propagation or 2^2 when taking account of sending and return of a signal between reader and transponder (Equation 1). With wave propagation in the interior of buildings the value can deviate because of, among other things, the multidirectional expansion of waves (Goldsmith 2005). Determining an empirical function for the RSSI course within a test environment with conditions deviating from the ideal free space propagation is enabled by Equation 3. Hereby, the constant K represents the above-mentioned RSSI influence factors and t the squared path loss exponents (Goldsmith 2005). The RSSI is well suited as parameter for comparison of different transponder types and test variants because a high RSSI shows a high reception security and also a high reading range (Catarinucci et al. 2012).

$$\mathrm{RSSI\ [mW]} = P_r G_r^2 G_t^2 \lambda^4 L (4\pi d)^{-4} \qquad \text{(Eq. 1)}$$

$$\mathrm{RSSI\ [dBm]} = 10\ \log_{10}(\mathrm{RSSI\ [mW]}) \qquad \text{(Eq. 2)}$$

$$\mathrm{RSSI\ [dBm]} = 10\ \log_{10}(K d^{-t}) \qquad \text{(Eq. 3)}$$

Test procedure

An overview of all trials and tested parameters is given in Table 1. In a preliminary test, reader positions relative to the test bench were first of all varied to determine the influence of changes in the trial surroundings or, in this case, the transmission direction of the reader before conducting further trials. In all further trials the reader position and the surrounding conditions were not altered. Investigated in these trials were the reproducibility of the measurements, the influence of the polystyrene ear tag holders, and the influence of the coordinate sequence on the results. Following this, a trial was conducted to compare six types of transponder ear tag. The matrix size for all the trials described here was established at 15 cm. According to Jungk (2010), measurement points for analysis of an UHF-RFID system should not be further than a half wavelength from one another. This represents 17.2 cm at a working frequency of 868 MHz and was fulfilled by the selected matrix size. The pause period between automatic positioning of the transponder and activating the reader represented 500 ms, the reading time at each coordinate, 1000 ms. To limit the number of readings, a period of 200 ms was established for resetting the transponder in the anti-collision process so that, per coordinate, a maximum of five readings could take place. In all the trials, the standard position of the reader was in the middle of the test bench with horizontal transmission plane (Figure 1). The middle of the reader antenna was at the same height as the middle of the transponder (165 cm). In the standard set-up, x and y-axes in the operational area of the reader represented those of the test bench. Only when positioning the reader at the side of the test bench, turned 90° to standard direction (Table 1, "90° to the left of the test bench"), were both axes exchanged from the reader aspect. The coordinates were moved to in sequence, in each case in a positive y direction and starting with positive x values (from the reader aspect) (Table 1, "in sequence, y rising").

Table 1: Overview of trials

Investigated parameters	Reader antenna position relative to test bench	Reproducibility of results	Ear tag holder	Sequence of coordinates	Transponder ear tag type comparison
Variants	central (standard) shifted 85 cm to left 90° to the left of the test bench	–	ear tag free ear tag completely embedded in polystyrene foam	randomised in sequence, y rising in sequence, y falling in sequence, x rising in sequence, x falling	–
Transponder type (number of examples)	A (1)	A (11) B3-4 (14) B4-4 (17)	A (6) B3-4 (6)	A (6) B3-4 (6)	A (6) ZT (6) B3-4 (6) B4-4 (6) C1 (3) C1-4 (3)
Orientation of transponder to reader antenna	5	5	3 5	5	1 2 5
Coordinate area [cm]	x: -165 to 165 y: 40 to 385	x: 0 y: 40 to 385	x: 0 y: 40 to 385	x: -165 to 165 y: 40 to 385	x: -165 to 165 y: 40 to 385
Test blocks	–	2	6	6	6
Number of test runs	3	84	48	60	90

In all trials, the ear tags were fixed in the required orientation in slits made in polystyrene foam blocks (Figure 2 a) and b)). The orientation numbers presented here agree with those from Hammer et al. (2015). The transponders or ear tags in all trials were positioned with the front side facing the reader (direction 5). For testing the influence of the ear tag holders of polystyrene, the transponder was not fixed in a polystyrene block in the "free" variant, but instead fastened in the same position with only thin wooden pegs on a base of polystyrene foam (Figure 2 b)) . The wooden pegs were hereby positioned on the outer edge of the ear tag to prevent any overlapping with the transponder. The aim of this way of fixing the ear tags was the realisation of a reference variant whereby no influencing of measurements by the holder could be assumed. With this trial, the transponders were also tested in sideways position in order to investigate a possible variation in ear tag holder influence in various directions (orientation 3). In the trial for comparing the various transponder types, the transponders were additionally to orientation 5 also tested in orientation 1 (sideways positioned opposite to orientation 3) and in orientation 2 (from underneath).

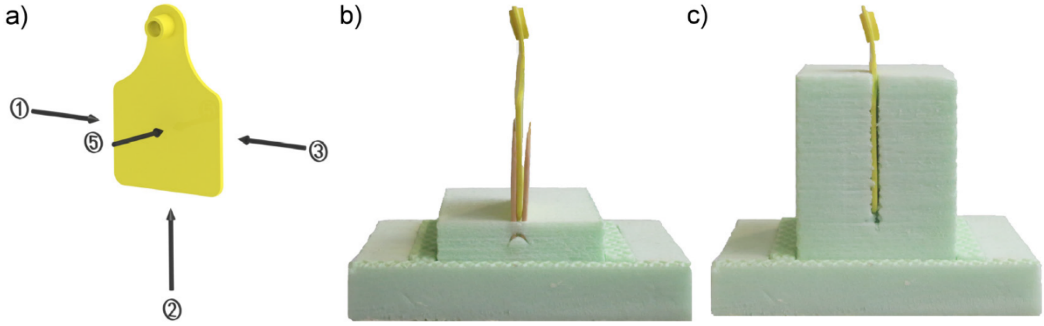

Figure 2: a) Illustration of ear tag orientation to reader (main transmission direction of reader represented by arrows); b) ear tag in "free" positioning (reference variant) in orientation 3; c) ear tag in polystyrene block in orientation 3.

Table 2: Overview of UHF transponders used with ear tags

Transponder type	**Characteristics**
A	– commercially available (UPM Web®) – folded dipole antenna structure – affixed to cattle ear tag (FlexoPlus®, Caisley International GmbH, Bocholt)
ZT	– commercially available (Smartrac Web®) – folded dipole antenna structure – embedded in air-filled pocket in cattle ear tag
B3-4, B4-4	– developed in research project – PIF antenna structure – base foil material: polyimide (Kapton®) – variation of resonance frequency (B4-4 > B3-4) – size designed for cattle ear tag – grouted into cattle ear tag (Primaflex®, Caisley International GmbH, Bocholt)
C1, C1-4	– developed in research project – PIF antenna structure – variation in base foil material: C1: self-adhesive aluminium foil (simultaneously antenna material) C1-4: polyimide (Kapton®) – size designed for pig ear tag – grouted in cattle ear tag (Primaflex®, Caisley International GmbH, Bocholt)

In the trials ear tags with six different transponders (A, ZT, B3-4, B4-4, C1, C1-4) were used (Table 2). All types used are of passive construction therefore supplied with energy from the reader antenna field only. Transponder type ZT is equipped with a U-code G2iL® chip (NXP Semiconductors Netherlands N.V.), all other transponder types with a Monza 4® (Impinj Inc.) chip. The transponders were prepared for working at 868 MHz. Type A is a commercially available passive UHF label transponder (UPM Web®), optimised for use in logistics. It has a high maximum reading distance of approx. 5 to 9 m (UPM RFID 2011). Additionally, because of its folded dipole structure it features a symmetrical directional characteristic (Detlefsen and Siart 2009, UPM RFID 2011), that offers advantages for methodical testing. For all further trials with the projects' own transponders, this transponder is seen as suitable comparison type for statistical evaluation, enabling a common evaluation of different trials despite possible changes in trial environment conditions. Type ZT is a newer generation of type A that is integrated in a cattle ear tag. The types B3-4, B4-4, C1 and C1-4 are functional examples developed in the research project for application in cattle and pig ear tags. They all have a PIF antenna structure

(Planar Inverted F-Shaped Antenna) (Fujimoto and Morishita 2013). Types B3-4 and B4-4 differ in the length of the last antenna section and thus in their resonance frequency. These variations were included for matching transponder antennas to frequency shift through the grouting into a plastic ear tag and through the attachment to respective animals. The types C1 and C1-4 differ only in the basis material of their antennas. The antenna structural material of all six transponder types was aluminium. More detailed information on design and size of the project's own transponder antennas are not possible because of patent legislation.

A prototype with internal antenna (deister electronic GmbH, Barsinghausen) was used as reader. Working frequency was 865.7 MHz. The effective radiated power (ERP) in all trials was 1 W or 30 dBm by circular polarisation and opening angle of 90°. The communication between reader and transponder took place via EPC class 1 generation 2 specifications (GS1 EPCglobal Inc. 2013).

Trial planning, data processing and statistical evaluation

No statistical trial planning was prepared for the preliminary trial to demonstrate the influence of an altered reader position on measurements. Only three reader positions were tested with a transponder example in this case. With all further trials, the trial plan was so designed that an evaluation of data was possible with a linear mixed model. Trial procedures were blocked to be able to allow for a possible timely alteration in the environment conditions. In the trial concerning reproducibility of the measurements, the blocks simultaneously represented both conducted repeats. In every complete randomised trial block was tested every example of each participating transponder type in every variant. Table 1 shows an overview of the number of individual test runs and transponder examples in every trial. The examples of the transponder ear tags represented the repeats of the transponder types in the trials, while the up to five individual readings of a transponder per coordinate were measurement repeats relating to the RSSI. In the statistical evaluations of the trials, the measured RSSI was applied as dependent variable. In a first analytical step, the average value of the RSSI from up to five readings (measurement repeats) was calculated for every coordinate on which the corresponding transponder was read. However, these coordinate averages were spatially correlated. For this reason the statistical evaluation was calculated from the RSSI coordinate averages, giving a total average for every test run. In this way, there emerged a statistically independent value for comparison of test runs. For arriving at the total mean value, only measurements of the RSSI on the line $x = 0$ were evaluated, because only on this line was the selected orientation of the transponder to reader antenna exactly conformed to. In the remainder of the recognition field the lateral shift of the transponder on every coordinate caused a slightly altered direction of transponder to reader and that is why, for the recognition area of a transponder in general, only a graphic evaluation is practical. Where only of interest is the average RSSI of the transponder in a certain direction, then the measurements can be restricted to the line $x = 0$ (Table 1).

Calculated from the RSSI total mean values in every test was a mixed model with the statistic package SAS 9.2 and the procedure MIXED. In each case the model creation was started with the full model with all double and triple interactions. Table 3 shows an overview of the fixed effects applied and the, after eventual withdrawal of non-significant effects or interactions, models resulting. The random effect in every model was the transponder example. Thus, eventual production-linked differences between the examples in the models could be considered. The normal distribution of the measurement values was present in all tests and was determined via Q-Q plots graphic analysis. In that the transponder types showed differences in their RSSI scatter no variance homogeneity could be achieved. Therefore, the transponder types were determined as grouping variable in the analysis and an own variance component per transponder type estimated. Comparisons of means were conducted with t-tests. There followed a Bonferroni correction for multiple comparisons of means.

Table 3: Overview of fixed effects and final mixed models in trial evaluations

Trial	Reproducibility of results	Ear tag holders	Sequence of the coordinates	Type comparison transponder ear tags
Fixed effects in the starting model	transponder type (T), repeat (W)	block (B), transponder type (T), orientation (A), ear tag holder (OH)	block (B), transponder type (T), coordinate order (K)	block (B), transponder type (T), orientation (A)
Final model	RSSI = T + E + r	RSSI = B + T + A + OH + T · A + T · OH + A · OH + E + r	RSSI = T + E+ r	RSSI = B + T + A + T · A + E + r

E = transponder example
r = residual error

The trial for determining reproducibility was additionally evaluated by graphically applying the Bland-Altman method (Bland and Altman 1986). In this form of evaluation, the difference between two repeats of the same measurement on the same measured object (transponder ear tags) is plotted against the mean value from both repeats. The mean value of all differences d is, with a given reproducibility, (near) zero and identifies a systematic error in the measurements through a deviation from zero. Further, it applies in the case of normal distribution of the differences that 95 % of the value lies within the area of 1.96 times the standard deviation s. This is demonstrated in the diagram through two lines by $d \pm 1.96 \cdot s$. Thus, the limits of agreement of both repeats and the so-called reproducibility coefficient ($1{,}96 \cdot s$) were determined and give an indication of how great the difference between two trial variants at least must be, so that this difference can be detected with the presented measurement procedure (Bland and Altman 1986).

Results and discussion

Exemplary detection field and RSSI course

First of all, in Figure 3 is presented for general information the RSSI test results collected in the presented test bench for an ear tag with an example of the transponder type B3-4 in the entire detection area and on the line x = 0. The measurements come from one run of the trial for testing the influence of the coordinate sequence. Clearly detectable is a RSSI reduction up to a distance of approx. 250 cm from the reader antenna in y direction. In greater distances, the RSSI would be significantly influenced through reflections in the trial environment and the resultant interference. RSSI fluctuations and gaps in the detection area can be seen in the outer areas in both presentations. However, it was very possible to match a regression curve according to Equation 3 to the data (adjusted R-squared $R^2 = 0.95$). The resultant path loss exponent t lay, with 2.6, in a plausible range for multiple expansion in interior areas (Goldsmith 2005). The basic requirements for the test bench, the measurement of detection field and signal strength from UHF transponder ear tags, could thereby be fulfilled.

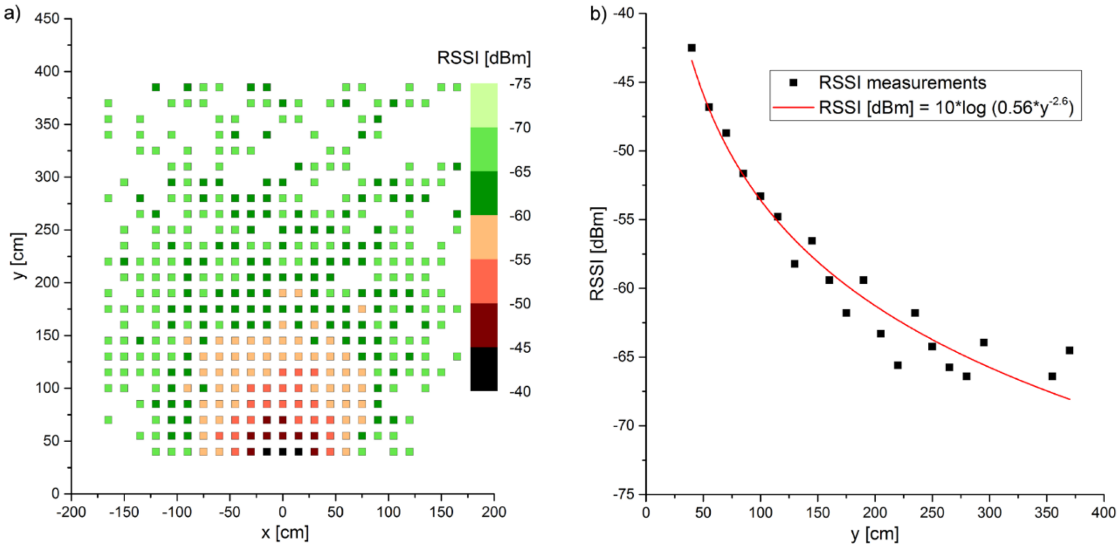

Figure 3: RSSI [dBm] in the detection area of a transponder ear tag with the transponder type B3-4 a) detection field (magnified presentation of the point measurements) b) measurements on the line x = 0 with regression curve

Influence of reader position

The influence of trial environment on recordings was clearly shown through alterations in reader antenna position relative to the test bench. The progression of the RSSI on the line x = 0 changed with the reader position (Figure 4). A progression that was a little more uniform was achieved at the position sideways to the test bench. Especially marked differences between the variants occurred, above all, from a distance of 200 cm from the reader. This indicated that, in the case of increasing distance between transponder ear tag and reader, the transmitted signal of the reader antenna or the reflected signal of the transponder is received via differing paths of the multiple expansion (reflections). In order to keep these always uniform and thereby enable reproducible results, an unchanging reader antenna position is therefore absolutely necessary. Furthermore, this trial emphasises that changes in trial environment can also change resultant measurements (Goldsmith 2005). Within a trial, systematic changes that occur can be taken into account through time-related block building. As already mentioned in the chapter Materials and Methods it is, however, necessary for the comparison of different trials to integrate a transponder type as statistic reference, or as comparative basis, in all trials.

As shown in the following mixed models presentation, some results appear that are in agreement. At first, the block effect was never significant, indicating only small changes of conditions during the trial. In addition, significant in every model were the transponder type and, in so far as this was validated, the orientation of ear tags as well as the interaction of orientation of ear tags and transponder type. These effects will be addressed in the results of transponder ear tag type comparisons. Discussed in the following trials are only the effects decisive to trial issues.

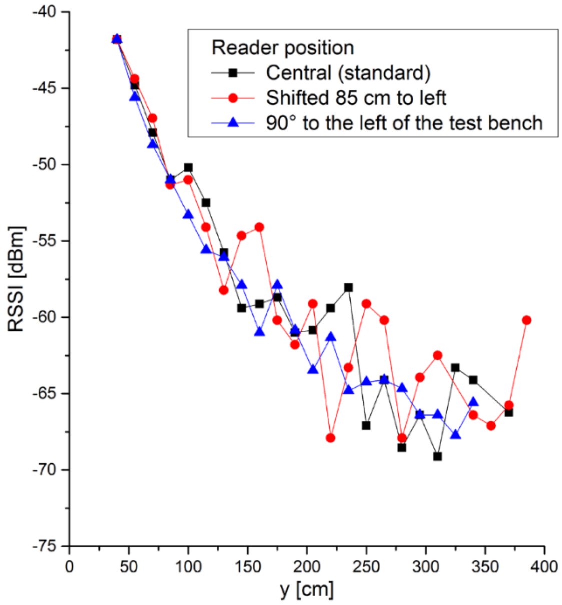

Figure 4: RSSI [dBm] of a transponder ear tag, transponder type A on the line x = 0 with altered position of reader antenna to test bench

Reproducibility

In the creation of the mixed model for this trial, the influence of reproducibility on the results was not significant (Table 4).

Table 4: Type III test of the fixed effects for the mixed model of the trial for determining reproducibility

Effect	Numerator deg. of freedom	Denominator deg. of freedom	F-statistic	P
Transponder type (T)	2	38.8	694.04	< 0.0001

The mean value difference between repeat 1 and repeat 2 for the total mean values of the RSSI was only 0.03 dBm. In the Bland-Altman analysis, this value represents the mean value of differences between repeats (Figure 5). The reproducibility coefficient lay by 0.18 dBm. Only one difference showed a higher result (0.42 dBm). On the individual coordinates, the differences between the two repeats for all transponder types and examples averaged 0.19 dBm with a standard deviation of 0.24 dBm. Hereby, it must be recognised that, through the mean value creation from (in most cases) five single measurements on every coordinate, the scatter of these mean values is lower by the factor than the single measurements. The scatter of the single measurements thus lay by approx. 0.42 dBm. The reader manufacturer gives as factory tested figure approx. 1.0 dBm as guideline value (Maass 2015). The results presented here indicate that precision of readers used in this trial was markedly better when considering the occurrence of imprecisions within the trial construction. In summary, the results show that, with the chosen trial design and the reader used, a good reproducibility of test bench measurements resulted. With regard to applied method one can, however, be critical about the limited scope of the tested types of transponder ear tags. It cannot be completely ruled out that the reproducibility of the results concerning very low signal strength transponder types (< -70 dBm) is poorer than the ones tested here. This is because measurement values in this case are in the vicinity of the lower limits of the reader measurement capability (Maass 2015). For this reason, reproducibility in trials

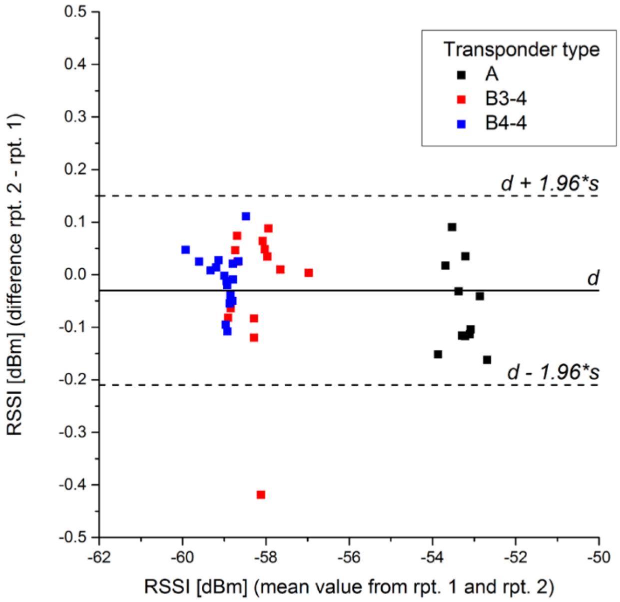

Figure 5: Bland-Altman diagram of trial for determining reproducibility; d = mean value, s = standard deviation of the differences between repeats 2 and 1

with such transponders should be tested once again. Such tests should also take place when another reader is used for the measurements.

Influence of the ear tag holders

Significant in the mixed model of the trial for determining the influence of the ear tag holders were, alongside the effects of the transponder type, orientation of the ear tag and interaction of these, also the effects of the ear tag holder and interaction between transponder type and ear tag holder as well as the interaction of ear tag holder and transponder orientation (Table 5).

Table 5: Type III test of the fixed effects for the mixed model of the trial for determining influence of ear tag holders.

Effect	Numerator deg. of freedom	Denominator deg. of freedom	F-statistic	P
Block (B)	5	4.3	2.66	0.1708
Transponder type (T)	1	5	203.95	< 0.0001
Orientation (A)	1	18.8	707.58	< 0.0001
Ear tag holder (OH)	1	18.8	8.47	0.0090
T · A	1	18.8	562.06	< 0.0001
T · OH	1	18.8	9.57	0.0060
A · OH	1	17.8	11.31	0.0035

A more precise observation of the influences of ear tag holder on the ear tags with both transponder types A and B3-4 showed that only with the type A was there a significant influence of holder on RSSI (Figure 6). The mean value of all measurements of ear tags with transponder type A with holders of polystyrene foam was 0.6 dBm higher than the mean value without holder. With type B3-4 the mean values were identical. The interaction of ear tag holders and orientation of ear tags showed a significant difference of 0.5 dBm between reference variants and polystyrene holders in orientation 5. With orientation 3, on the other hand, there was no significant difference between the two variants. A cause could not be found for the different influence of the ear tag holder on signal strength of the two transponder types. It must be emphasised, however, that the difference for transponder type A is very low in relation to the mean value (approx. 1 % of mean value). Despite this, possible causes are discussed in the following.

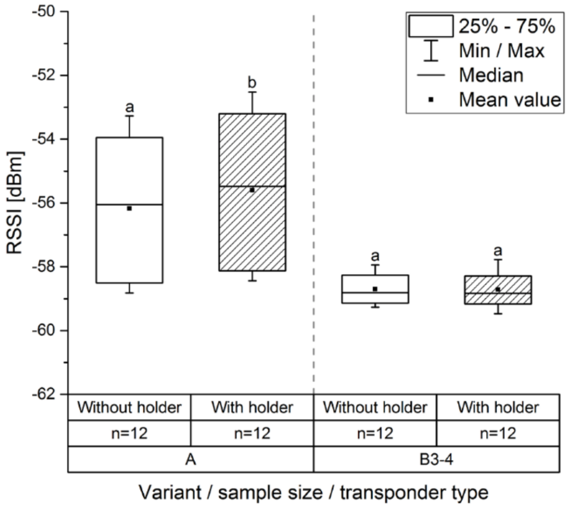

Figure 6: RSSI [dBm] of the ear tags with transponder types A and B3-4 with and without holder of polystyrene foam; n: sample size; a, b: different letters within a transponder type indicate significant differences ($P < 0.05$)
Influence of coordinate sequences

The shift in resonance frequency of the transponder type A through the surrounding holder can be almost ignored for two reasons. One, such a strong influence is not plausible for polystyrene foam because the material has a very low permittivity (Webster and Eren 2014). Secondly, this would also lead to an expected similar influencing of transponder type B3-4, in that both transponders are adapted for use with materials of high permittivity (Rao et al. 2005, UPM RFID 2011). For the same reason, a negative influence of the wooden pins used in the “free“ presentation of the ear tags is also to be excluded. A different influencing of both transponder types through minimally different orientation and position of the ear tags in the “free“ fixing variant is theoretically possible. Should this be the case, then the effect would cease to appear with constant use of the polystyrene holding system. In relation to the different influences of transponder holders in orientation 5 and 3 this effect is also the most plausible, but also ceases through continual application of the polystyrene blocks only. The application of only two different transponder types for the test presented here can also be judged as uncritical in that the conclusions reached also exactly apply for all other UHF transponder types. In summary, it can be concluded that an application of ear tag holders of polystyrene foam only influenced test bench results to a limited extent. Furthermore, the use of these materials allows high reproducibility of position and orientation of ear tags and is therefore preferable to fixation by wooden pins. Thus, in the tests with the ear tags as described here without further electromagnetic influence and, for instance, in trials for determining influences of ear tissue on transponders, polystyrene foam can be used as material for holding ear tags and ear tissue.

Influence of coordinate sequences

An influence on trial results through the sequence of coordinates could not be determined. The corresponding effect in the mixed model was not significant (Table 6). Only the transponder type had a significant effect on the results. The agreement of measurement values with all five variants of the sequence can be explained through the switching-off the reader field between the measurements on two coordinates. If the reader transmits continually, the effect shown with passive UHF transponders is a greater reading distance by the transponder in the case of a movement out of the reading field compared with movements into the field (hysteresis). This can be explained through the required amount of energy for activating the transponder chip being higher than the cut-off threshold. If the reader is switched off between two coordinates this effect disappears because the transponder cannot store energy continually (Derbek et al. 2007, Knop 2014). The use of only two different transponder types for the trial presented here should be assessed uncritically because the described effect occurs for every UHF transponder with commercially available chips. This knowledge means that time savings can be achieved in further trials through starting-off coordinates in order, giving shorter paths compared with a randomised coordinate sequence.

Table 6: Type III test of the fixed effects for the mixed model of the trial for determining the influence from the sequence of the coordinates

Effect	Numerator deg. of freedom	Denominator deg. of freedom	F-statistic	P
Transponder type (T)	1	10	487.02	< 0.0001

Comparison of different types of UHF transponder ear tags

Tested in this trial was the use of the test bench for comparing ear tags with different transponder types in differing orientations. In the mixed model, the evaluation showed significant influences from transponder types, orientations to reader and their interactions (Table 7).

Table 7: Type III test of the fixed effects for the mixed model in the trial comparing different types of UHF transponder ear tags.

Effect	Numerator deg. of freedom	Denominator deg. of freedom	F-statistic	P
Block (B)	5	18.7	0.32	0.8976
Transponder type (T)	5	17.7	407.06	< 0.0001
Orientation (A)	2	35	159.09	< 0.0001
T · A	10	18.2	128.43	< 0.0001

Closer observation of the differences between the transponder types with comparisons of means resulted in a division of types into three groups (Figure 7). The highest average RSSI achieved the ear tags with transponder types A and ZT. Between these two types, a significant difference could be determined. This indicates that the inclusion of the transponder type Web® within an air-filled pocket in the ear tag (ZT) caused no difference in signal strength compared with the adhesion system (A). There were also no significant differences between types B3-4 and B4-4. These were of identical size and form, differing only in a minimal adjustment through which the type B4-4 showed a slightly higher resonance frequency than the type B3-4. This difference showed no influence on the respective measurements at the ear tags. It has to be determined in practical trials whether the transponders return different performances during use on animals. In the third group were the ear tags with transponder types C1 and C1-4. With these, the average RSSI was significantly lower. The difference for these transponders that are designed for use as pig ear tags, compared with the others in cattle ear tag size, could be explained through their smaller antenna area. Otherwise, design and form were similar to types B3-4 and B4-4. The larger the UHF transponder, the higher, as a rule, is the transmitting distance (Catarinucci et al. 2012). Additionally, a lower scatter of measurements with type C1-4 in comparison with type C1 was noticeable, possibly explained by the better constructional quality of the former through its base polyimide foil allowing more even grouting into the ear tag compared with the pure aluminium antenna of type C1. Possibly this leads to reduced scatter between the examples of these type, which also brings with it advantages in practical use.

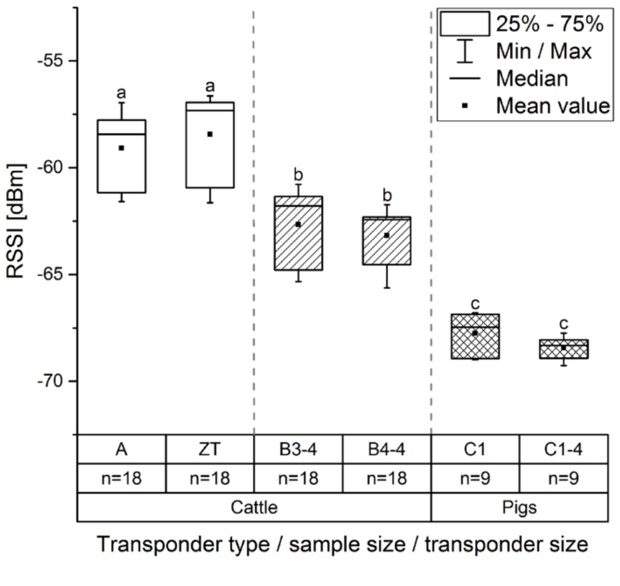

Figure 7: RSSI [dBm] of the tested ear tag types; n: sample size; a, b: different letters show significant differences (P < 0.05)

Presented in Figure 8 are the simulated directional characteristics of the ear tags with the three basic transponder types from the above-mentioned groups. These illustrated in red show orientations where transponder types in combination with the plastic ear tags produced a high signal strength and transmission distance. On the other hand, green and blue areas indicate poorer performance.

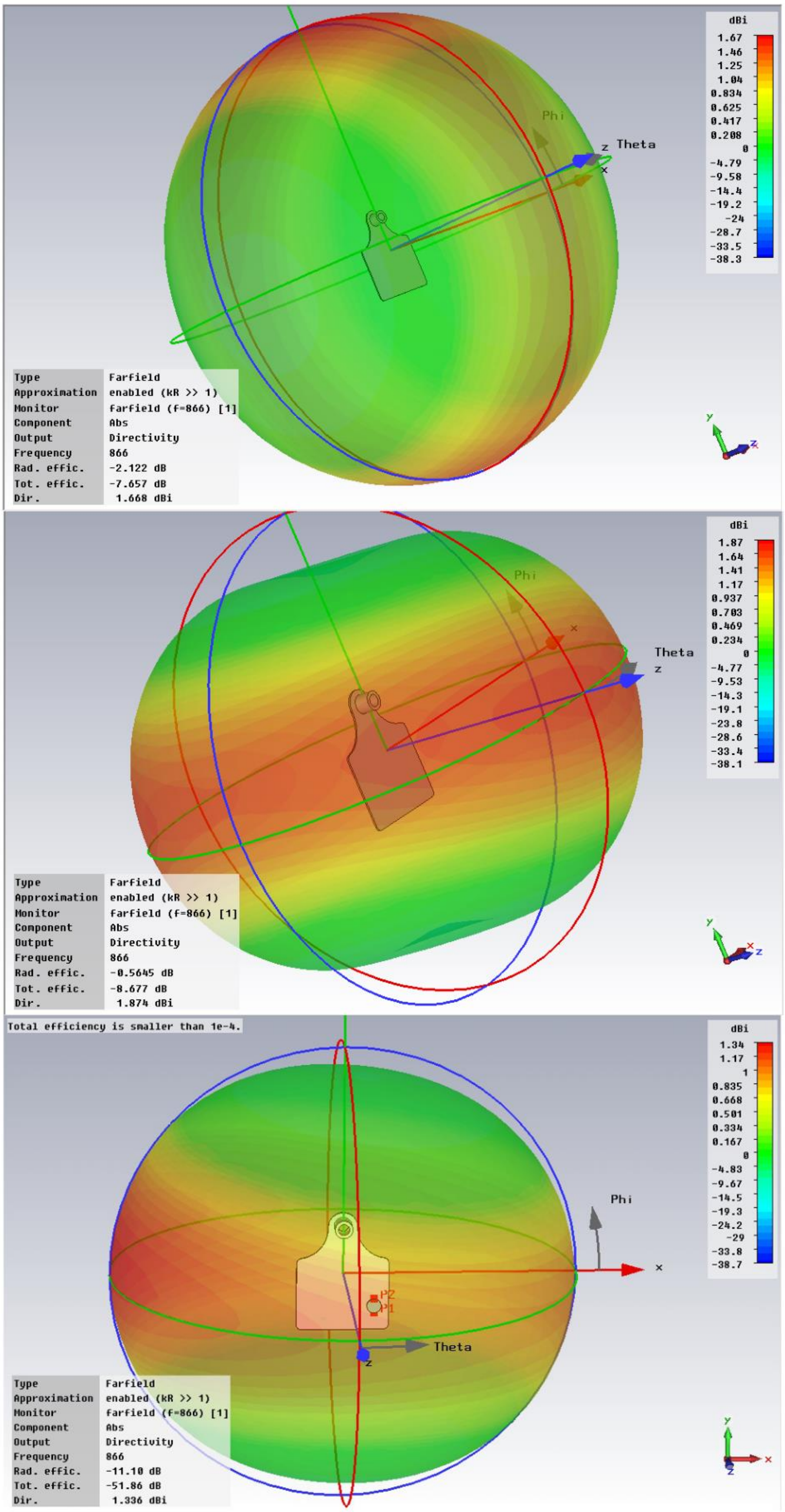

Figure 8: Simulated directional characteristics of ear tags with three basic transponder types (from above: types A and ZT; types B3-4 and B4-4; types C1 and C1-4) (simulation and illustration: deister electronic GmbH, CST Microwave Studio)

A comparison of means was carried out for every transponder type to determine differences of the three tested orientations to the reader (Table 8). With one exception, the measurements on the static test bench determined orientation with the respective highest and lowest signal strength in agreement with the simulation for every transponder type. Only with type ZT was orientation 5 shown to be better than with orientation 2. This could not be explained with the simulation. According to the simulation, orientation 2 should achieve a slightly higher signal strength. Possibly this difference could have been caused by the influence of the air pocket in the ear tag. This was not taken account of in the simulations. With the types B3-4 and B4-4 orientation 1 and orientation 5 were determined best orientation, in simulation as in trial. With C1 and C1-4 no significant statistical difference between the two orientations was determined in the test bench trial. However, measurement values showed, analogue to simulation, a bit higher signal strength in orientation 1. The orientations with lowest signal strengths with all transponder types given in the simulation were repeated in the test bench results. With types A and ZT this was orientation 1, with all the others, orientation 2.

Table 8: RSSI [dBm] of the ear tags according to transponder type and orientation to reader antenna on the test bench; n: sample size; a, b: differing letters within a line indicate significant differences ($P < 0.05$)

Transponder type	**Orientation 1**	**Orientation 2**	**Orientation 5**	**n**
A	-61.3^{c}	-57.7^{a}	-58.3^{b}	6
ZT	-61.1^{b}	-57.4^{a}	-56.8^{a}	6
B3-4	-61.8^{a}	-65.0^{b}	-61.3^{a}	6
B4-4	-62.3^{a}	-64.9^{b}	-62.3^{a}	6
C1	-66.9^{a}	-69.0^{b}	-67.5^{a}	3
C1-4	-67.9^{a}	-69.1^{b}	-68.2^{a}	3

The trial comparing different types of UHF transponder ear tags confirmed that a comparison is possible between ear tags with different transponder types but also that comparison of individual orientations within the types and between the types is possible. An assessment of the transponder types on the test bench before testing on animals is helpful in allowing a preselection and interpretation of results from practical tests (Hammer et al. 2013). The measurement of signal strength and reading distance in separate orientations has also been recognised by other authors as important. Catarinucci et al. (2012) and Jungk (2010) emphasise that a transponder for versatile application and reliable identification in, if possible, all directions should be able to demonstrate uniform readability. None of the transponder types tested here satisfied this requirement. The reason is that transponder form and size restrictions for the planned application often lead to antenna structures with marked sensitivity regarding their orientation to the reader. Most used for UHF transponders are folded dipole antennas or loop antennas. Both are strongly directed (Derbek et al. 2007, Ng et al. 2005). However, this has also advantages in that the effective transmission distance of the transponders oriented in the main transmission direction is greater than that of a similarly-shaped directional characteristic with the same size of transponder. Because not all directional characteristics are symmetrical there should, in addition to the three orientations tested here, be at least another three compared in the opposite orientation in future, so that a comparison taking account of the entire directional characteristic is possible.

Conclusions

The aim of the tests was determination of suitability of the presented test bench for comparing different types of UHF transponder ear tags in individual as well as in all orientations. The basic requirement for the test bench, the measurement of detection area and signal strength of UHF transponder ear tags, was achieved. The methodical trials carried out indicated a good reproducibility of the measurements where position of the reader was constant. The ear tag holding system featuring polystyrene foam had no relevant influence on the RSSI measurements. Also, the sequence of coordinates, where measurements took place, did not influence the measurement results. The possibility of comparing the RSSI of transponder types in various orientations was proven with various types of UHF ear tags in the concluding comparison. A comparison with simulated directional characteristics for the tested transponder types resulted in a very good agreement of results from the simulation and the test bench for different orientations of the transponders. Thus, in summary, all the necessary requirements were fulfilled by the test bench. However, it must be emphasised that with this method no absolute measurements of transponder or ear tag characteristics are possible and that the recorded results can be influenced through changes in the trial environment. To cope with this situation, a suitable statistical experiment plan is required. Furthermore, the conclusions reached regarding reproducibility of results apply only to the respective reader used. A change of reader means that relevant parameters must be recalculated. In addition, reproducibility in the tests of the transponder types with very low RSSI must be assessed separately.

The next step will feature comparative investigations of different function examples of UHF transponder ear tags especially optimised for use with cattle and pigs. Furthermore, the measurement of influences of ear tissue and tissue imitations in the vicinity of ear tags on signal strength and field of recognition will take place. Additionally, trials are planned that have as target a limitation of the reading area in different positions and alignments of reader antennas. Through this, important parameters for monitoring of barn zones such as feeding or lying areas, for health monitoring of animals are to be investigated before use in barns. Finally, the practicability of a system for localisation of UHF transponder ear tags should be investigated. Furthermore, an additional application of the presented test bench featuring measurement of detection areas with LF and HF transponders would be reasonable in that the test bench covers normal reading distances in such systems and also because, in the frequency ranges involved, environment influences can be more easily minimised than in the UHF area.

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CHAPTER 2

NOVEL APPROACH TO DETERMINE THE INFLUENCE OF PIG AND CATTLE EARS ON THE PERFORMANCE OF PASSIVE UHF-RFID EAR TAGS

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Novel approach to determine the influence of pig and cattle ears on the performance of passive UHF-RFID ear tags

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ABSTRACT

The potential of passive ultra-high frequency radio frequency identification (UHF-RFID) as an electronic identification technology for precision livestock farming applications has been evaluated in different projects. Despite very promising advantages, such as a high read range and simultaneous identification of animals, the application of UHF transponders in ear tags still struggles with the strong influence that body tissue in the vicinity of the transponders has on the reading performance of the system. A detailed and precise investigation of the influence of ears on the transponder ear tags to support transponder development is hardly possible in on-farm tests with animals. Thus, the aim of this study was to develop an approach to measure the influence of pig and cattle ears on the received signal strength indicator (RSSI) and read range of UHF transponder ear tags on a test bench. In a second step, replacement of cattle and pig ears in the experiments with tissue models was tested to enhance the repeatability and comparability of results. Three sets of tests were performed with three different types of UHF transponders (1) to compare the influence on the read range and RSSI of the transponders at the front and back of pig and cattle ears, (2) to determine the repeatability of measurements with ears, and (3) to compare the influence of pig ears with that of two tissue models. Results showed significant differences between the front and back side of the ears for pig ears with better results at the back. The results for cattle ears were heterogeneous. The repeatability of measurements was low in all variants (front and back of pig and cattle ears) with repeatability coefficients of up to 10 dBm (RSSI) and 217 cm (read range). The tests generally demonstrated the strong and highly variable influence of ear tissue on the read range and RSSI of the transponders. Nevertheless, the results indicated that targeted detuning of UHF transponders can lower the influence of ear tissue on the reading performance, which is promising for the use of UHF-RFID in livestock farming. The method presented could be used in an optimised manner in the future to perform comprehensive tests and comparisons of different types of UHF transponder ear tags.

1. Introduction

Precision Livestock Farming (PLF) technologies and applications have been in the focus of research in recent years. Increased animal welfare, sustainability and efficiency are the core aims of this approach (Berckmans, 2008). A prerequisite for the linkage of animal data to PLF systems is an animal identification system that allows for automation and is affordable for the farmer (Banhazi et al., 2012). Low frequency radio-frequency identification (LF-RFID; 134.2 kHz) is a well-established technology for animal identification and can be considered as standard for mandatory identification and for management purposes on farms (Rossing, 1999; Trevarthen and Michael, 2008; Passantino, 2013). The most common way to attach LF transponders to animals are ear tags, followed by collars, injectable transponders and ruminal boluses. Nevertheless, LF-RFID has two major disadvantages: a low read range (<1 m) and a low data transmission rate preventing efficient use of anti-collision algorithms (Burose et al., 2010; Ruiz-Garcia and Lunadei, 2011; Finkenzeller, 2012).

Several projects have emerged in recent years which have tested the application of passive ultra-high frequency RFID (UHF-RFID; 860–960 MHz) for electronic animal identification with ear tags (Moxey, 2011; Stekeler et al., 2011; Baadsgaard, 2012; Federal Office for Agriculture and Food, 2012; Hogewerf et al., 2013; Pugh, 2013). All of them utilised the high read range (up to 8 m) and ability of UHF-RFID for quasi-simultaneous detection of transponders with anti-collision algorithms to put batch-reading of animals and efficient traceability into practice. Activity and behaviour monitoring for typical Precision Livestock Farming

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applications can also be carried out with UHF-RFID (Adrion et al., 2015a, 2016). The general perspective for this technology in animal husbandry is very positive, and is also supported by a fast technical development and decrease of costs (Umstatter et al., 2014; Das and Harrop, 2016). However, the application of UHF transponders in ear tags still struggles with the strong influence that body tissue near the transponders has on the reading performance of the system. This effect makes reliable and constant detection of the animals difficult and raises the need for targeted UHF transponder development for animal identification (Baadsgaard, 2012; Hogewerf et al., 2013; Hammer et al., 2016).

1.1. Technical background

An overview of function, performance measurement and limiting factors of UHF-RFID systems is given in the following to provide background for the assessment of the measurement results presented.

1.1.1. Function and performance measurement of UHF-RFID systems

A passive UHF-RFID system consists of a reader with an antenna transmitting a radio frequency signal to a transponder. The transponder itself is composed of an antenna and an integrated circuit chip (Nikitin and Rao, 2006a). The transponder does not have its own source of energy, but instead, gains the energy for operation of the chip from the electromagnetic field of the reader antenna (Finkenzeller, 2012). The UHF-RFID works with electromagnetic coupling between reader and transponder in the far-field and backscatter modulation for communication from the transponder to the reader. The transponder antenna collects energy for the transponder chip (coupling) and reflects part of the radiation back to the reader (backscatter) depending on the chip input impedance. Data transfer is performed both ways (uplink, reader to transponder, and downlink, transponder to reader) via signal modulation, in most cases, amplitude shifting. The transponder modulates the reflected signal by switching of the chip input impedance between two states (Nikitin and Rao, 2006b; Chawla and Ha, 2007; Finkenzeller, 2012). A successful reading of a transponder takes place when the data stored on the chip memory, in most cases the unique identification number of the transponder, is transferred to the reader (Finkenzeller, 2012).

Performance parameters, such as the read range, are not often measured directly to evaluate UHF transponders. The transponder sensitivity, meaning the lowest power level that is needed to turn on the transponder chip and to communicate in both directions, is measured instead. This measurement is typically performed in an anechoic chamber to increase measurement accuracy (Nikitin and Rao, 2006b; Derbek et al., 2007; European EPC Competence Center, 2011; Barge et al., 2014). From this measurement, a theoretical read range can be calculated for the transponder. However, in many cases, the performance of the whole UHF-RFID system consisting of the reader, the transponder and the operating environment is of interest, leading to model-type laboratory tests representing a part of the practical application (Jungk, 2010; Mainetti et al., 2013; Adrion et al., 2015b). The read range in these tests, i.e. the maximum distance at which a transponder can be read, is very important as a main performance measure of the UHF-RFID system. This is due to the need of high read ranges in most of the applications, giving the possibility of reducing the number of readers needed (Lorenzo et al., 2011). Looking more closely, there are two different read ranges, the uplink and the downlink range, of which the lower one is the actual range of the transponder (Lorenzo et al., 2011). The uplink read range is limited by the chip sensitivity, meaning the minimum power the transponder chip needs to operate, and the amount of energy that is transferred from the transponder antenna to the chip (Nikitin and Rao, 2006a). The downlink read range is limited by the reader sensitivity and the power reflected by the tag (Loo et al., 2008). In most cases, reader sensitivity is much higher (around −70 to −90 dBm) than chip sensitivity (around −10 dBm), so that the uplink energy transfer is limiting read range (Perret, 2014). It should be mentioned that chip sensitivity is normally predefined by its manufacturer, thus, the performance of a transponder with a given chip can be optimised mainly by optimising the transponder antenna. Most UHF-RFID readers can measure the so-called received signal strength indicator (RSSI). In addition to the read range, the RSSI is a second easy-to-measure performance indicator for UHF-RFID systems. It is a reader-specific indicator of the received power reflected by the transponder. It is dependent mainly on the distance between the reader and transponder, and also, among other factors, on the reader output power and the antenna gain of reader and transponder antenna (Choi et al., 2009; Adrion et al., 2015b). It allows for a relative ranking of the transponder performance under different conditions, for example, on or next to different materials. A comparison between transponders is also possible when transponders have the same chip module. Basically, a higher RSSI indicates a higher probability of a successful reading of the transponder (Catarinucci et al., 2012), but due to the influence of interference the comparability of transponders by means of RSSI can be limited in some cases.

1.1.2. Influence of external materials on UHF-RFID transponder performance

Factors determining the power a UHF-RFID transponder antenna can reflect to the reader and transmit to the chip are influenced directly by the materials to which the transponder is attached. A transponder optimised typically for use in free air shows a decreased read range when being used on a certain material (Rao et al., 2005a). Without changes to the transponder chip or antenna, this effect can only be reduced by increasing the distance to the material, e.g. with a spacer (Park and Eom, 2011). The reduction of the read range near a material is caused by a decrease of the transponder antenna gain (so-called gain penalty) due to currents induced in the adjacent material. Additionally, the currents in the material cause a change in the directional gain pattern of the transponder (Griffin et al., 2006; Lorenzo et al., 2011). This leads to a changed read range depending on the direction from which the transponder is viewed. The second main effect on the transponder is a change in the antenna impedance because of the permittivity of the material nearby. Consequently, a mismatch between antenna and chip impedance occurs, causing a lower power transmission coefficient and a changed backscattering coefficient at the given operation frequency (Nikitin and Rao, 2006b). An optimum impedance match between antenna and chip is reached when the antenna input impedance is equal to the complex conjugate of the chip impedance, so that the power transmission coefficient τ is at its maximum $\tau = 1$ (Rao et al., 2005b; Nikitin and Rao, 2006b; Loo et al., 2008; Perret, 2014). The energy transfer from the transponder antenna to the chip at this frequency is also maximum. The materials near the transponder lower the transponder resonance frequency at which the impedance matching and, thus, the highest read range is achieved (Rao et al., 2005a). Reversely, through targeted detuning of the UHF transponder antenna, the transponder can be adjusted for use on a certain material. For example, shortening the antenna length may increase the transponder resonance frequency (Rao et al., 2005a). It should be mentioned that the chip impedance is dependent on the frequency and input power. The transponder antenna is normally tuned to chip impedance at the minimum input power the chip needs to operate, thus, a high read range is achieved. Consequently, also when the transponder antenna is tuned correctly, reading gaps can occur through impedance mismatch within the regular read range of the transponder (Nikitin and Rao, 2006b). Transponder chips with the possibility of automatic tuning of the chip input impedance at every power-up event have been released recently. These chips are able to change their impedance according to changes in the antenna impedance, so that optimum transponder performance can be reached in a certain range of materials' influence (Impinj Inc., 2014). Of course, changes in the antenna geometry for tuning purposes influence other antenna parameters, thus, UHF transponder design is always a compromise between maximum gain, impedance match and targeted antenna bandwidth (Nikitin et al., 2005). A detailed concept of the antenna design process for UHF-RFID transponders is given by Rao et al. (2005a).

The main properties of the materials influencing the transponder performance are the so-called loss tangent (tan δ), which represents the energy losses due to induction of currents in the material, and the relative permittivity (ε_r), which causes the impedance and, thus, resonance frequency shift of the transponder antenna (Griffin et al., 2006; Lorenzo et al., 2011). Operation of UHF transponders in the vicinity of meat or body tissue is a major challenge, because of the high loss potential of these materials. Griffin et al. (2006) calculated a relative permittivity of $\varepsilon_r = 50$ for an amount of 11 × 22 × 1 cm of ground beef. The loss tangent is given with $\tan\delta = 0.7$. This results in a measured average gain penalty of 10.2 dB at a frequency of 915 MHz, which is equal to the uplink power loss of the folded dipole antenna tested on the meat. Nguyen et al. (2013) reported measurements of $\varepsilon_r = 56–62$ and $\tan\delta = 0.3–0.4$ for beef. Peyman et al. (2005) measured the relative permittivity of the skin of pigs around 50 kg liveweight between 35 and 45 (*in vivo* and *in vitro*). In comparison to this, typical plastics, such as polyvinylchloride or polyethylene, to which UHF transponders are often attached in logistics applications, have a much lower relative permittivity of $\varepsilon_r = 2–4$ and a tangent loss of $\tan\delta = 10^{-5}–10^{-2}$. It is important to point out that the negative influence of tissue very near to a transponder cannot be compensated for completely, thus, a transponder will always have a better performance in free air when it is tuned correctly.

1.1.3. Other influences on the performance of a UHF-RFID system

In addition to the influence of materials, the surroundings of the reader and transponder also influence the reading performance through constructive and destructive interference (small-scale fading) or absorbing obstacles in the propagation path. The interference is caused by waves reflected from surfaces creating a multipath environment (Goldsmith, 2005; Griffin and Durgin, 2009). A polarisation mismatch between reader and transponder antennas can also limit the performance of the system (Griffin and Durgin, 2009). Consequently, the physical communication process between reader and transponder is very complex and the performance of a UHF-RFID system can only partly be predicted in a specific environment. A detailed overview of the factors contributing to the link budget of a backscatter RFID system is presented by Griffin and Durgin (2009) and Nikitin and Rao (2006a).

1.2. Problem definition

The study presented here was part of a research project with the aim of developing passive UHF-RFID transponder ear tags and readers for electronic identification of pigs and cattle (Federal Office for Agriculture and Food, 2012). During the transponder ear tag development process, laboratory tests were performed (Adrion et al., 2015b; Hammer et al., 2015) as well as on-farm tests of applications, such as simultaneous detection or hotspot monitoring of animals (Adrion et al., 2015a; Hammer et al., 2016). These on-farm tests were very helpful to confirm the overall performance of transponder ear tags and the whole UHF system in practice.

The high potential of ear tissue to influence the reading performance of a UHF transponder ear tag inevitably has to be taken into account in the development process. However, a detailed and precise investigation of the influence of ears on the transponder ear tags and a continuous tracking of the adjustment of the UHF transponders during the development process is hardly possible in tests with animals. The constantly changing environment in the barn, the individual behaviour and the dynamic movement of the animals only allow for measurements such as detection rate and sensitivity of detection. This raised the question whether there is a possibility of testing the performance of different transponder ear tags under the influence of animal ears with simple methods in the laboratory. Additionally, the intensity and characteristics of the influence of ears or ear tissue on the performance of UHF transponder ear tags has not yet been described in literature and is of strong interest for UHF ear tag development.

1.3. Objectives

Consequently, the objective of this study was to develop an approach for testing the influence of pig and cattle ears on signal strength and read range of UHF-RFID ear tags on a test bench used for transponder evaluation in the project. The degree of influence on these performance measures was of interest to draw conclusions for the development and use of UHF transponder ear tags, especially for the optimisation of transponder antennas. In a second step, the possibility of replacing cattle and pig ears with tissue models was to be tested because of the strongly limited shelf life of the ears and the limited inter-comparability of test results due to variations in the shape and size of the ears.

2. Materials and methods

2.1. Experimental outline

A total of three main test sets were conducted with three different types of UHF transponders encapsulated in or glued onto ear tags:

(1) Measurements of RSSI and read range were made with pig and cattle ears, comparing the positioning of the transponder ear tag at the front and back side of the ears.
(2) The results of these tests led to four tests in the second set in which the repeatability of the measurements was determined for the front and back side of pig and cattle ears.
(3) In the last test set, the RSSI and read range of the three types of transponders were compared in free air with pig ears and two types of tissue models, namely electromagnetic phantom blocks and cellulose-cotton cloths soaked in isotonic saline solution.

2.2. Test bench

All tests in this study were conducted on a static test bench developed for measuring the reading area and signal strength of UHF transponder ear tags (Fig. 1). It should be emphasised that the test bench was not placed in an interference-free environment (anechoic chamber), thus, there were influences on the measurements from reflections and absorption of the radiation of the reader in the surroundings of the test bench. Therefore, the test bench represented an operation environment typical of a barn with a concrete floor and metal parts, so that the UHF ear tags were evaluated under semi-laboratory conditions. The function of the

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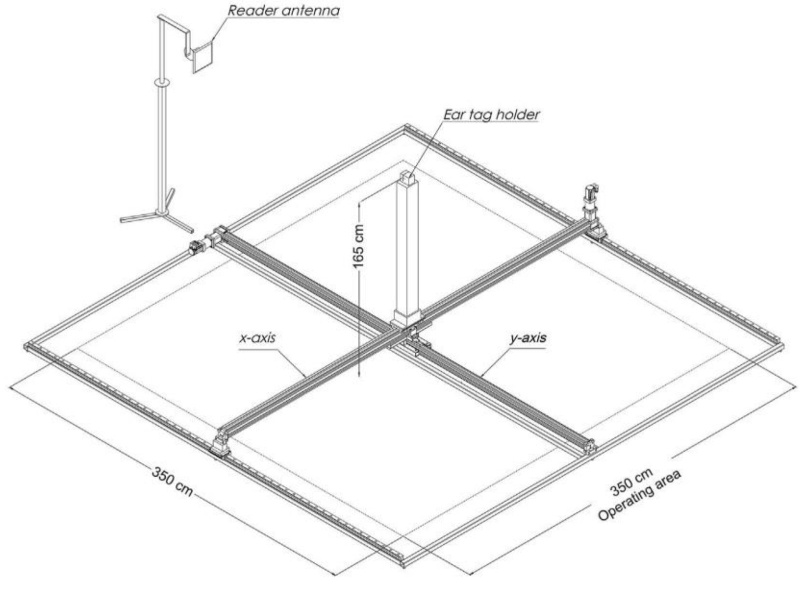

Fig. 1. Model of the static test bench.

test bench, its measurement characteristics, the robustness to the interference from the surroundings and the repeatability of the measurements were described in Adrion et al. (2015b) in detail.

The main elements of the test bench were two linear drives which allowed the positioning of the ear tags within an area of 3.5 × 3.5 m with an accuracy of 1 cm. The ear tags were placed on a pillar of extruded polystyrene 165 cm above the floor. This material has almost no electromagnetic effect (relative permittivity $\varepsilon_r = 1.03$), ensuring low influence on the measurements (Webster and Eren, 2014). The UHF-RFID reader (model TSU 200, deister electronic GmbH, Barsinghausen, Germany) was placed in front of the test bench at the same height as the centre of the transponder ear tags. The UHF-RFID reader worked at a frequency of 865.7 MHz with an effective radiated power (ERP) of 1 W (30 dBm) and circular polarisation. The opening angle of the antenna was 90°. The communication between reader and transponder followed EPC class 1, generation 2, specifications defined by ISO 18000-6C (GS1 EPCglobal Inc., 2013).

During the tests, measurements were made on a line directly in front of the reader antenna (x = 0). The position of the reader allowed measurements from 40 to 385 cm distance to the reader. A spacing of 15 cm between the measurement coordinates was chosen, resulting in a total of 24 coordinates per test-run. At each coordinate, the slide carrying the transponder holder was stopped and, after a pause of 500 ms, the reader was switched on for 1 s. The maximum number of readings was set to five per second (200 ms reset time of the inventoried flag in the anti-collision algorithm). Static measurements were performed in this manner at each of the coordinates, while moving the ear tag away from the reader step by step. Accordingly, each test-run testing one ear tag in combination with one of the materials or ears tested contained up to 5 × 24 measurements of the RSSI, which was recorded with every reading. A number of measurements lower than five could occur at coordinates with poor energy supply of the transponder. The measurement accuracy of the RSSI was at least 1 dBm (Adrion et al., 2015b). The read range of the ear tag in each test-run was recorded as a second and more important metric for the performance of an ear tag. It was defined by the farthest coordinate where a successful reading of the transponder took place.

2.3. Transponder types

Three different types of transponder were chosen for the tests, two of which were developed during the research project. One of these was designed and sized for use in cattle (type B5, transponder size approx. 50 × 50 mm) and one for use in pigs (type C2, transponder size approx. 30 × 40 mm). Due to restrictions in the ear tag development process, both transponders were encapsulated in an ear tag sized for cattle (Primaflex®, Caisley International GmbH, Bocholt, Germany). The transponders were integrated into the ear tag by injection moulding. Both transponder types had a planar inverted F-shaped (PIF) antenna structure made of copper on polyimide foil. They were (de-)tuned to a resonance frequency higher than 868 MHz to compensate for impedance mismatching through the plastic of the ear tag and the ear tissue. More information on the tag design cannot be given because of relevance for patent protection. A detailed description of the transponder types B5 and C2 in the context of the development during the project is given in Hammer et al. (2015) and Hammer et al. (2016). The third transponder type is a commercially available label transponder (type A, UPM Web®, transponder size 30 × 49 mm) with a folded dipole antenna, optimised for use on plastic (UPM RFID, 2011). Thus, this transponder was detuned by the manufacturer similarly to the transponder types B5 and C2. It was glued onto a cattle ear tag (FlexoPlus®, Caisley International GmbH, Bocholt, Germany) for the tests in this study. All three transponder types were passive transponders and equipped with a Monza® 4D chip (Impinj Inc., 2015). These three transponder types were chosen with the aim of comparing the influence of the ears on transponders with different antenna sizes and to compare the transponders developed in-house with a transponder from a different field of application, but also adapted for use on plastic and/or other materials.

2.4. Ears and tissue models

The UHF ear tags were tested in combination with pig ears and cattle ears as well as two tissue models, namely electromagnetic phantom blocks and cellulose-cotton cloths soaked with isotonic saline solution. The ear tags were tested in free air as a reference variant (Fig. 2). The pig and cattle ears were purchased from an abattoir. The cattle ears were fresh and untreated, while the pig ears could only be taken after scalding and depilation. The ears were cooled to approx. 1 °C and tests were started directly to prevent changes in the characteristics of the ears as far as possible. The ears were also cooled between the test-runs during a test.

The ear tags were fixed onto the polystyrene holder with thin wooden pins (toothpicks) in all variants to ensure a constant position. It was shown in Adrion et al. (2015b) that the pins do not influence the RSSI of the ear tag. A typical position for the ear tag on the animal in practice was chosen for both types of ear. The ear tag was always in the centre of the holder and, thus, in line with the centre of the reader antenna. A stable position of the ear tag was also maintained relative to the ears. The ear tags were placed in front of the pig ears at a point two thirds of the distance away from the tip to the base of the ear. For the cattle ears, the position was chosen at half of the distance between the tip and the base. With this positioning, the ear tag and ear were not in complete contact and, in most cases, there was a small distance between the ear and some parts of the ear tag (approx. 1–5 mm or 1/350 to 1/70 of wavelength at 868 MHz) due to the uneven form of the ears. This also represents the typical situation of this type of ear tag on an animal's ear.

The electromagnetic phantom blocks (EM phantoms) were blocks of a material based on silicone and carbon, which is used, for example, as a substitute for human hands in tests on mobile phones (Schmid und Partner Engineering AG, Zurich, Switzerland; Schmid und Partner Engineering AG, 2016). Its relative permittivity was approx. ε_r = 29.5 with an approx. standard deviation of 3.6 at a frequency of 868 MHz, according to the certificate of the material test. Blocks of 150 × 100 × 10 mm were used in the tests. Because of the high costs of this material, an alternative was sought. Considering that the major part of the electromagnetic influence of ears is caused by the tissue fluids, cellulose-cotton cloths for household use soaked in isotonic saline solution (0.9% NaCl) were chosen for the tests (Priva®, manufactured for Netto Marken-Discount AG & Co. KG, Maxhütte-Haidhof, Germany). Isotonic saline solution has a relative permittivity of approx. ε_r = 75 at 868 MHz (Pethig, 1987). It was expected that the permittivity of the solution was lowered by the cloths, similar to the effect of cell membranes in body tissue (Pethig, 1987). The cloths were used in two layers. After adding 120 g of the saline solution, the cloths were vacuum sealed in polyamide/polyethylene bags, resulting in a block of 195 × 150 × 10 mm. A slice of polystyrene (thickness 3 mm) the same size as the ear tags was placed between the tissue models and the ear tags in the tests to ensure a comparable positioning of the ear tags relative to these materials and the positioning in front of the ears (Fig. 2).

2.5. Statistical test design and data analysis

Both RSSI and read range were considered for data analysis for all tests. The data for the read range did not need any processing. Regarding the RSSI, at first, an average per coordinate was calculated from the single measurements at each coordinate (up to five, see Section 2.2). These values were used for graphic evaluation. To do a statistical analysis without spatially correlated measurements for the RSSI, one value per test-run was obtained by calculating an average RSSI from the averages at the coordinates measured during the test-run. The values of both variables were rounded to whole numbers to meet the level of measurement precision.

2.5.1. Statistical analysis for comparison of ear tag positioning at the front and back side of pig and cattle ears

Two tests were conducted for comparison of the positioning of the transponder ear tags on the inside and outside of ears, one with pig ears and one with cattle ears. A randomised complete block design was created for both tests. The three types of transponders were tested with eight different ears. Six randomised complete blocks were created, each block testing one sample of each type of transponder on each of the eight ears at the front and back. A total of 144 test-runs per test were performed. The statistical analysis was carried out with a mixed model for RSSI and read range separately (procedure MIXED, SAS 9.4®, SAS Institute Inc., Cary, NC, USA). The type of transponder (B5, C2, A), the block (1–6), the positioning (front, back) and the interaction between type and positioning were taken as fixed effects. The transponder samples (1–18) and ears (8 samples) were modelled as random effects.

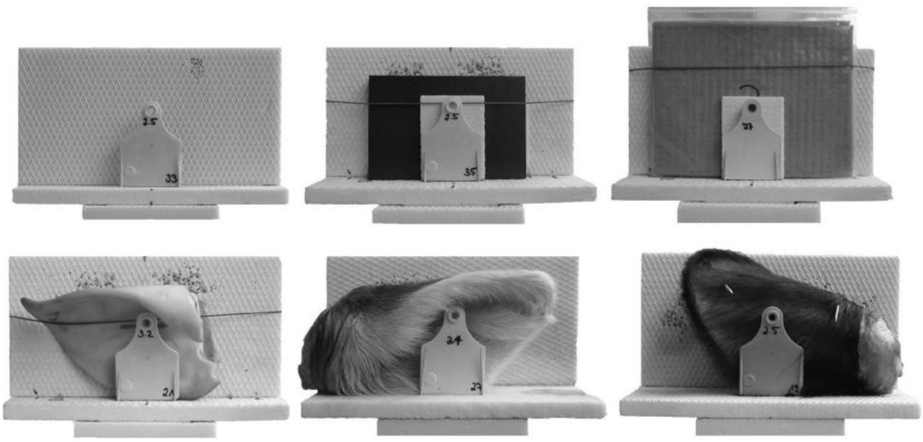

Fig. 2. Mounting of the transponder ear tags onto the polystyrene holder in combination with different materials. From top left to bottom right: free air, electromagnetic phantom block (Schmid und Partner Engineering AG, Zurich, Switzerland), cellulose-cotton cloth (Priva®, Manufactured for Netto Marken-Discount AG & Co. KG, Maxhütte-Haidhof, Germany) soaked in isotonic saline solution, pig ear (front), cattle ear (front), cattle ear (back; back of pig ear analogous).

The mixed model allowed for heteroscedasticity between the types of transponder. Non-significant effects were removed from the model during the analysis. The normal distribution of the studentised residuals and their homoscedasticity were confirmed graphically using QQ-plots and plots of residuals versus predicted values. Homoscedasticity of the studentised residuals verified correct modelling of the present heteroscedasticity between transponder types. Comparisons of means were conducted using the Edwards-Berry procedure for controlling the family-wise type I error rate at a level of α = 5% (Edwards and Berry, 1987).

2.5.2. Statistical analysis for the test of repeatability of measurements

A test design with two randomised complete blocks was used to estimate the repeatability of the measurements of RSSI and read range of transponder ear tags next to ears. Twelve transponder samples of each of the three types were tested twice (once per block) with a single ear. Thus, each block contained 36 single test-runs, resulting in 72 test-runs per test. A total of four tests were conducted, estimating the repeatability of the measurements on pig and cattle ears with the ear tags attached at the front and back of the ears. The results were analysed graphically by the Bland-Altman method (Bland and Altman, 1986). For this purpose, the difference between the two test-runs (replicates) for each transponder ear tag sample was plotted against the mean of both test-runs. The mean of all differences and the mean ± 1.96 × standard deviation were computed for the evaluation of repeatability. The 1.96-fold of the standard deviation is also called the "coefficient of repeatability" (Bland and Altman, 1986). This coefficient was calculated for all three types of transponder together without accounting for possible heteroscedasticity between the types.

2.5.3. Statistical analysis for comparison of the influence of pig ears and tissue models

A resolvable incomplete block design (alpha design) was created with CycDesigN (VSN International Ltd., Hemel Hempstead, UK) for three experiments (randomisations), which together constituted the third test. In each experiment, four samples of each of the three types of transponder were tested with four types of material (see Section 2.4). Each of the materials was represented by a different number of specimens. In particular, these were two EM phantoms, six cellulose-cotton cloths soaked in isotonic saline solution, ten pig ears (front of ears only) and two replications of a reference variant in free air, resulting in a total of 20 specimens (treatments). The three types of transponder were assigned to one of the replicates of the alpha design in each experiment. The four different samples of each type of transponder were then considered as incomplete blocks of that one replicate and, hence, were assigned to five of the treatments each, so that each type of transponder was tested once with all treatments in each experiment. This resulted in 60 single test-runs for the three types of transponder per experiment. The 60 test-runs were completely randomised in each experiment. As there were three experiments, there were 180 test-runs for the whole test. Twelve samples of each type of ear tag were tested in each of the three experiments, resulting in a total of 36 ear tags tested.

The statistical analysis was carried out with a mixed model for RSSI and read range separately (procedure MIXED, SAS 9.4®). The experiment (1–3), the type of transponder (B5, C2, A), the material (free air, EM phantom, cloth, pig ear), and the interaction between type and material were taken as fixed effects. The samples of the types of transponder (1–36) and the treatments (1–20) were set as random effects. Residual variance was allowed to differ between types of transponder and material. Non-significant effects were removed from the model. Confirmation of normal distribution of the studentised model residuals and their homoscedasticity, as well as the comparisons of means were conducted analogous to the first tests (Section 2.5.1). Homoscedasticity of the studentised residuals verified correct modelling of the present heteroscedasticity between types of transponder and material.

3. Results and discussion

3.1. Comparison of ear tag positioning at front and back side of pig and cattle ears

The results of the first tests with pig ears showed significant differences between the front and back side of the ears (Table 1). Both RSSI and read range were higher at the back side for ear tags with transponder type B5 and A. The differences in average RSSI were higher for type A (9 dBm) than for type B5 (3 dBm), but almost equal in average read range (156 cm and 158 cm, respectively). Type C2 showed the opposite behaviour: the measurements at the back were significantly lower than at the front side of the pig ears. Ear tags with transponder type C2 also had the lowest average RSSI (−65 dBm) and read range (105 cm) of all three types when looking at all test-runs at the front and back side of the ears. By contrast, type B5 performed best in terms of average RSSI (−58 dBm), while type A reached the highest average read range (247 cm).

The results of the measurements with cattle ears differed strongly from those with pig ears. No significant differences in average RSSI and only small significant differences in average read range could be detected between the front and back side of the ears for all three types of transponder (Table 2). A clear difference in read range of the front and back side was not visible, and the results differed with the type of transponder. Type C2 showed no significant differences between front and back. Most of the RSSI measurements with cattle ears were in the range of the measurements with pig ears for all three types of transponder. The average read range was higher for all types (in average 181 cm with pig ears compared to 220 cm with cattle ears). Type B5 and A had a higher read range at the back of pig ears than at the back of cattle ears. In contrast, type C2 showed an increased read range at the back of the cattle ears, but all types had a higher read range at the front of the cattle ears than at the front of the pig ears.

Another difference from the tests with pig ears was the number of test-runs with cattle ears where no reading of a transponder could be detected. Types B5 and A were not detectable in 1 out of 96 test-runs and type C2 was detectable in all 96 test-runs with cattle ears. In contrast to that, type A was not detectable in 4, type B5 in 7 and type C2 in 21 test-runs out of 96 test-runs with pig ears.

Looking at these first results, it is remarkable that the measurements of RSSI and read range of type B5 and A at the front side of the pig ears were clearly lower than all other measurements of these types. There are two possible explanations for this. Firstly, the round shape of the pig ears' top formed a kind of hollow space and cover above the ear tags, perhaps leading to a higher grade of absorption of multipath signals compared to the back of the ear and the cattle ears. This would have prevented additional energy supply for the transponders from reflections of the reader signal (Goldsmith, 2005). A generally higher absorption of radiation by the pig ears and a high loss tangent are also a likely explanation for the lower average read range of all transponders with pig ears and for the higher number of test-runs where no reading of a transponder was possible. The hair covering of the cattle ears could have had a possibly positive effect. It could have worked like a spacer between flesh and transponder and prevented losses through currents induced in the tissue. The same principle is used to increase the performance of UHF transponders attached on metal surfaces (Park and Eom, 2011).

Table 1
Pig ears: average RSSI and average read range of ear tags with transponder types B5, C2 and A at the front and back side of the ears; means followed by at least one common letter are not significantly different ($p < 0.05$).

Transponder type	RSSI [dBm] Side of ear		Read range [cm] Side of ear	
	Front	Back	Front	Back
B5	-59^b	-56^a	98^b	256^a
C2	-62^a	-67^b	121^a	89^b
A	-64^b	-55^a	169^b	325^a
All	-62^b	-59^a	130^b	232^a

Table 2
Cattle ears: average RSSI and average read range of ear tags with transponder types B5, C2 and A at the front and back side of the ears; means followed by at least one common letter are not significantly different ($p < 0.05$).

Transponder type	RSSI [dBm] Side of ear		Read range [cm] Side of ear	
	Front	Back	Front	Back
B5	-56^a	-56^a	296^a	202^b
C2	-64^a	-63^a	137^a	155^a
A	-61^a	-61^a	239^b	289^a
All	-61^a	-60^a	224^a	215^a

The second explanation for the low transponder performance is that a stronger or adverse contact between the ears and ear tags occurred at the front of the pig ears than on the back side of the ears or the cattle ears. This could have caused a stronger impedance mismatch between the transponder chip and antenna and, thus, a lower reading performance. In the worst case, the ear prevented any communication between transponder and reader, leading to test-runs without any reading. The differing results of C2 indicate that this transponder was influenced less negatively on the front side than on the back side of the pig ears. However, the decrease in read range was also higher for this transponder with pig ears than with cattle ears.

The generally lower performance of C2 in comparison with the other types of transponder can be explained by its smaller antenna geometry leading to less power that can be transferred from the antenna to the chip and be reflected to the reader (Catarinucci et al., 2012).

3.2. Test of repeatability of measurements

The results of the first tests showed high variances, therefore, the repeatability of the measurements with ears was of strong interest. The Bland-Altman plots of RSSI and read range with pig ears show clear differences between measurements at the front and back of the ears (Fig. 3). At the front of the ears, the coefficient of repeatability of the RSSI was 10 dBm, and at the back, only 2 dBm. The read range showed similar results. The coefficient of repeatability at the front of the ears was 169 cm and only 37 cm at the back. However, a strong outlier influenced the coefficient of read range repeatability at the front of the ear. Without this measurement, the coefficient was 71 cm. Only 5 out of 12 transponders of type B5 could be read in both replicates, while 7 of the transponders of C2 and all 12 of the transponders of type A were readable in both replicates at the front of the ears. Two transponders of type C2 at the back of the ears were read only in one replicate, while all the other transponders were readable in both replicates. The measurements of RSSI and read range in this test were comparable to those obtained in the first test, except for slightly higher RSSI measurements of type A at the back of the ears.

The measurements with cattle ears in this test were also within the range of the first tests (Fig. 4). Again, the measurements at the front and back of the ears showed similar results. The coefficients of repeatability were 8 dBm at the front and 5 dBm at the back, or 200 and 217 cm, respectively. All transponders in these tests could be read in both replicates, except for one exemplar of type A at the back of the ears.

The results show how strongly variable the influence of ears on the ear tags is. Even though these measurements were made with only one ear for each of the four variants (pig and cattle ears, front and back), the variance of RSSI and read range was very high. As a comparison, a repeatability coefficient of 0.18 dBm was measured in free air at this test bench with similar types of transponder ear tags (Adrion et al., 2015b). The repeatability coefficient of the read range in those tests was 0 cm (perfect repeatability), also measured with a coordinate grid of 15 cm. The large variances for measurements with ears can be explained by their flexible and varying shape and the impossibility of placing the ear exactly at the same position in each test-run. Consequently, the distance and contact between ear and ear tag differed slightly, but with a great effect on the reading performance. Of course, it is expected that the results will also differ with different ears.

The remarkably better repeatability of measurements at the back of pig ears leads to questioning the experimental set-up in this variant. The strongly convex form of the pig ears resulted in a slightly greater distance between the ears and ear tags at the bottom of the ear tags compared to the other variants. This probably lowered the degree of impedance change, energy losses and absorption of radiation around the transponders, leading to better performance (Griffin and Durgin, 2009; Park and Eom, 2011). This also applies to the results in the first test. In practice, it would be expected that a transponder on the back side of pig ears is influenced more than in the tests presented. An on-farm test comparing the attachment of the transponder ear tags at the front and back of cattle and pig ears is required to investigate whether the results from the present tests are also resulting, for example, in differing reading rates.

In summary, the measurements of repeatability show that the reading performance can vary considerably due to the influence of the ear tissue when using UHF transponders in ear tags. This effect is hardly predictable for the actual application, because of

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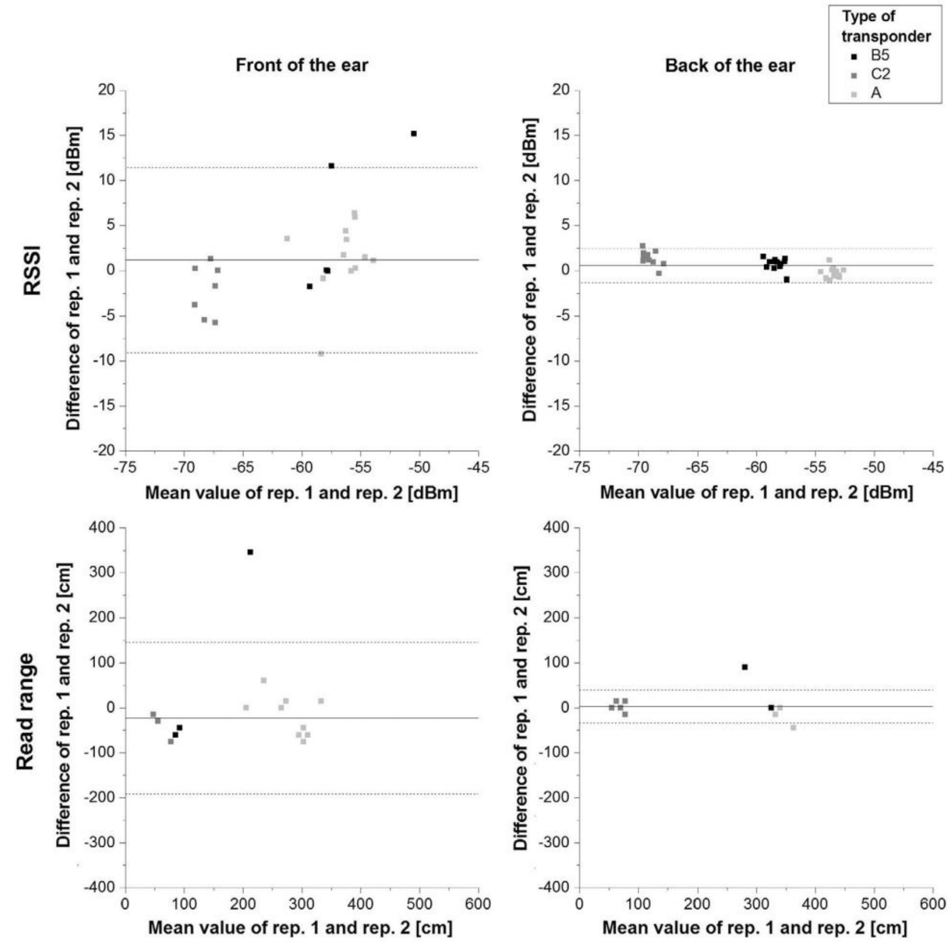

Fig. 3. Pig ears: repeatability of measurements of RSSI and read range of ear tags with transponder types B5, C2 and A at the front and back of the ears (Bland-Altman plots); solid lines: mean of the differences between repetition 1 and 2; dashed lines: mean of the differences ± 1.96 × standard deviation of the differences.

the varying shape and the dynamic movement of animals' ears. From this point of view, the reading of a UHF transponder can be seen rather as a stochastic than a controlled process. Nevertheless, a higher degree of repeatability than in the present tests is necessary for comparable testing under laboratory conditions, and constant characteristics, such as shape, size and electromagnetic properties of the ear or ear tissue model material, have to be ensured as is done in standard UHF transponder tests (Derbek et al., 2007).

3.3. Comparison of the influence of pig ears and tissue models

In the third test, measurements with pig ears were carried out in direct comparison with the transponder performance in free air to investigate the influence of the ears in detail. Additionally, the low repeatability of measurements and the high effort of keeping the ears fresh throughout the whole duration of the tests raised the need for testing of tissue models with similar effects on the UHF ear tags. The influence of pig ears and tissue models in the third experiment of the test (results representative for all three experiments) is shown in Fig. 5 based on RSSI curves from single test-runs. A reduction of the RSSI and read range in comparison to the reference measurements in free air was detected over all three types of transponders and over all materials (pig ears, EM phantoms and cellulose-cotton cloths soaked in isotonic saline solution). The only exception was type C2, which showed similar or even higher values of RSSI and read range with pig ears compared to those in free air in three out of ten test-runs with pig ears in experiment 3, and eleven of 30 test-runs with pig ears in total. The variance of measurements was highest for type A with pig ears. By contrast, type B5 showed the least variance with both pig ears and tissue models.

The measurements of RSSI and read range were generally lower with the tissue models than with the ears. This applied most for type A. Here, the ear tags were hardly readable with the EM phantoms and the cloths. In total, type A was readable at more than one coordinate only in two out of eighteen test-runs with the tissue models. All measurements of RSSI and read range with the tissue models were lower than in free air for type C2. No positive impacts, like with pig ears, could be detected here. The results for type B5 with tissue models matched the measurements with pig ears best in terms of RSSI, but a read range lower than in six out of ten test-runs with pig ears was measured with the tissue models.

The statistical analysis of all three experiments of the third test showed results similar to the graphic evaluation of experiment 3 (Table 3). The average read range represented the graphic results

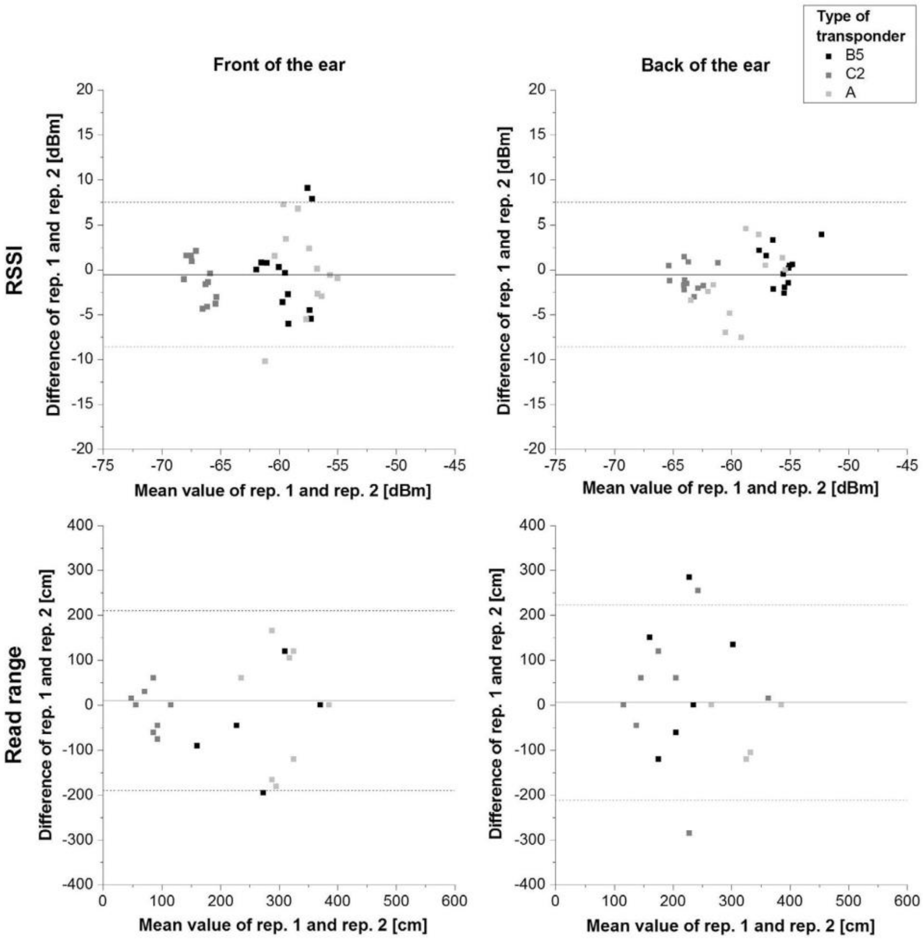

Fig. 4. Cattle ears: repeatability of measurements of RSSI and read range of ear tags with transponder types B5, C2 and A at the front and back of the ears (Bland-Altman plots); solid lines: mean of the differences between repetition 1 and 2; dashed lines: mean of the differences ± 1.96 × standard deviation of the differences.

very well, while with the average RSSI, some differences visible in Fig. 5, for example, between B5 in free air and with all materials, could not be discovered. The average read range was significantly lower with pig ears and with tissue models than in free air for all three types of ear tags. Significant differences could also be detected between the average read range with pig ears and with tissue models for type C2 and type A. No significant differences between the different materials could be detected for type B5. Additionally, no significant differences in average RSSI and average read range could be detected between the reference measurements in free air and the measurements with pig ears for type C2.

The results of the third test show that the pig ears and tissue models in most test-runs had a negative impact on the reading performance of the transponder ear tags with a high variance of the measurements with ears. This confirms the results obtained in other tests with applications of UHF transponders near materials (Rao et al., 2005a; Griffin et al., 2006; Lorenzo et al., 2011). The front side of pig ears was chosen for the present test, being the variant with the strongest influence on reading performance in the previous tests. Thus, the results of this test should be looked at as a worst-case scenario for the influence on UHF ear tag performance.

The comparatively high values of RSSI and read range of transponder type C2 in about a third of all measurements with pig ears were a remarkable exception in the third test. These results probably show the effect of the targeted detuning of this transponder to compensate for the impedance mismatch and, hence, shift of the transponder resonance frequency close to the ear tissue. When the transponder was in contact with the ear in such a way that the transponder worked at the target resonance frequency, the RSSI and read range of the transponder were higher than in free air. However, that this effect occurred only in about a third of all test-runs indicated that there was a majority of other positions of contact or vicinity to the ear that influenced the transponder negatively. Future tests should reveal which kind and location of contact is influencing the performance of this and other transponders positively. No test-runs with higher RSSI or read range with pig ears could be detected for type B5 and A, although these transponders were also detuned for use on dielectric materials. The detuning of these transponder types was probably not as strong as that of type C2, so that the negative impact of the tissue by absorption and gain reduction was stronger than the effect of resonance frequency shifting for type B5 and A in all test-runs.

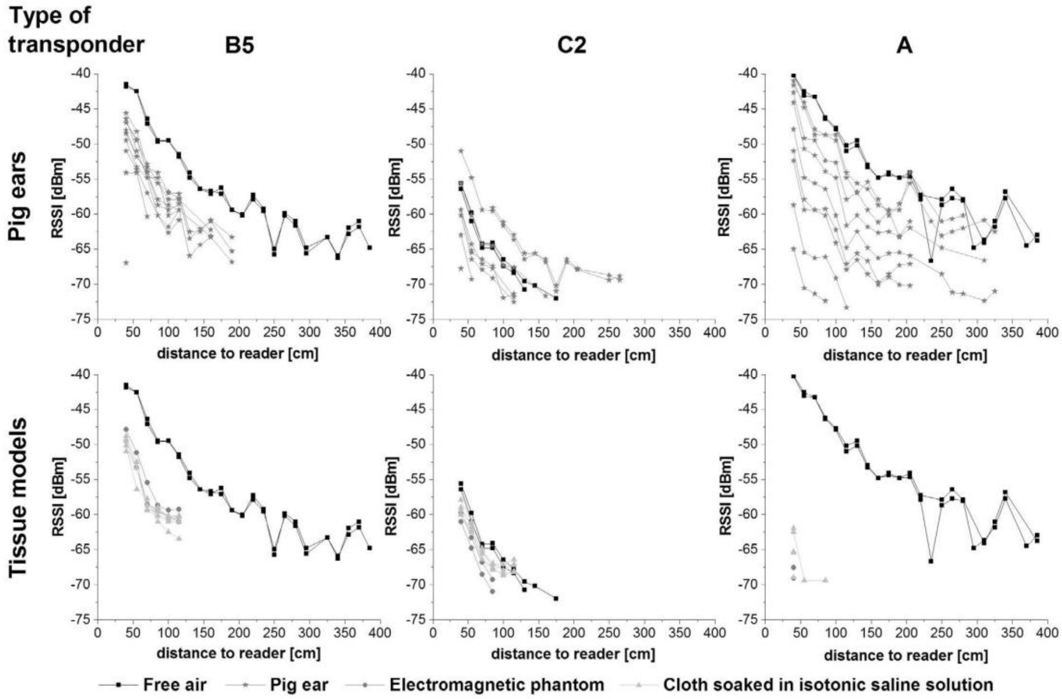

Fig. 5. RSSI of ear tags with transponder types B5, C2 and A depending on the distance to the reader and type of material in experiment 3 of the third test. Tested variants/materials: free air (reference), pig ears (front of ears), electromagnetic phantom blocks and cellulose-cotton cloths soaked in isotonic saline solution.

Table 3
Average RSSI and average read range of ear tags with transponder types B5, C2 and A tested in free air, with pig ears (front of ears), with electromagnetic phantom blocks and with cellulose-cotton cloths soaked in isotonic saline solution; means followed by at least one common letter are not significantly different ($p < 0.05$).

	RSSI [dBm]				Read range [cm]			
	Material							
Transponder type	Free air	Pig ear	Electrom. phantom	Cloth	Free air	Pig ear	Electrom. phantom	Cloth
B5	-58^{a}	-57^{a}	-56^{a}	-58^{a}	383^{a}	136^{b}	115^{b}	115^{b}
C2	-65^{a}	-65^{a}	-66^{a}	-65^{a}	138^{a}	138^{abc}	98^{c}	115^{b}
A	-55^{a}	-61^{b}	-68^{c}	-65^{c}	385^{a}	229^{b}	40^{c}	46^{c}
All	-59^{a}	-61^{b}	-63^{c}	-62^{c}	302^{a}	168^{b}	84^{c}	92^{c}

The tissue models did not represent the pig ears well. The reduction of variance compared to the measurements of ears was expected and desired, but the strong differences between the degrees of influence on the three types of transponder lead rather to the assumption that not all characteristics of the pig ears were represented correctly. The impact on read range and RSSI caused by the EM phantoms and the cloths soaked in isotonic saline solution was much too strong, especially for type A. The partly positive influence of the pig ears on type C2 could not be reproduced by the tissue models. A possible argumentation could be that the dielectric properties of the materials chosen may not fit the properties of the pig ears, but this does not explain the differences between the types of ear tag. The shape and size of the models could possibly be a decisive parameter in developing an artificial ear. Further tests must be carried out to find a suitable form and material to replace the ears.

4. Implications for UHF ear tag development and testing

Some conclusions can be drawn from these results. Because the contact with ears, even for type C2, had a negative influence on the reading performance in most of the test-runs, a UHF transponder for use in flexible ear tags should not be detuned too much, but should also work well in free air. It can be expected that the dynamic movement of the animals' ears will generate many positions of the ear tag where the influence of the tissue is small, thus, a high performance in free air is useful. Tests with similar transponder types on a test bench and of simultaneous detection of animals support this assumption. Transponders performing well in free air on the test bench also performed well with animals (Hammer et al., 2015, 2016). In addition, a broad bandwidth and an omnidirectional gain pattern of the transponder would make the transponder less sensitive to the influence of the ear and could compensate for small adverse effects of the ears (Lorenzo et al., 2011). By contrast, a stronger detuning of the transponder could be beneficial for rigid or button-type UHF ear tags, because of the direct and permanent contact of these ear tags to the ears. Tests should be carried out with this kind of ear tag to prove this hypothesis.

Another main conclusion from the results of the third test is that the replacement of the ears with tissue models is difficult.

Standard tests of UHF transponders are carried out with flat material samples similar to the shape of the tissue models used here (European EPC Competence Center, 2011), but for radiation measurements near human head and body standards for complex body phantoms, such as the Specific Anthropomorphic Mannequin Phantom, already exist (International Committee on Electromagnetic Safety, 2006). An extensive study with different shapes and materials is necessary to find a suitable model for pig and cattle ears. Also the influence of temperature on the electromagnetic properties of the ears would have to be studied first to ensure that the cooled ears used in the current experiment were a correct reference for ears of living animals (Peyman et al., 2005).

The results also indicate that the RSSI does not always represent the performance of the ear tags in terms of read range. Type B5, for example, showed a higher average RSSI with pig ears than type A, which instead reached a higher read range. A part of this difference results from the averaging of the RSSI over all coordinates, which leads to relatively high averages for transponders that are only read near the reader. Furthermore, also variations in RSSI due to interferences in the surrounding of the test bench impact the correlation between RSSI and read range negatively. However, the limited read range with simultaneously high RSSI also indicates that the impedance matching for type B5 was not optimal for low input power levels, thus, an impedance mismatch occurred with increasing distance to the reader, causing a limited read range (Nikitin and Rao, 2006b). In conclusion, the read range seems to be generally the more informative and decisive measure for transponder performance in UHF-RFID systems, whereas the RSSI is additional performance information, that should be analysed rather as a curve then by averaging over a certain read range.

5. Conclusions and outlook

The tests presented here investigated the influence of pig and cattle ears on UHF transponder ear tags for the first time. The results show a negative and highly variable influence of pig and cattle ears on the reading performance in terms of RSSI and read range of UHF transponder ear tags. The three types of transponders tested showed different responses to the proximity of animal ears. This indicates that the development of transponders with a targeted detuning, a broad bandwidth and omnidirectional reading characteristics could help to minimise the negative impact of ear tissue on the reading performance of UHF ear tags. The results, in connection with findings from on-farm tests, also suggested that the transponder ear tags should also have a good performance in free air, because many readings of flexible ear tags seem to be performed when the ear tag is not in contact with the ear.

Prior to the introduction of a new electronic identification technology for livestock, comprehensive field tests have to be carried out to prove its suitability, performance and durability (ISO TC23/SC19/WG3 Project Team on Additional Technologies, 2014). However, a laboratory testing process is desirable for tests during transponder development and for the benchmarking of UHF ear tags. The method to test UHF ear tags with pig and cattle ears presented in this study has a high potential to fulfil this task. Further studies and on-farm tests must be carried out to prove the representativeness of the current experimental set-up. Subsequently, comprehensive tests and comparisons of different types of transponders in different types of ear tags could be performed to support the development of UHF ear tags. In a second step, the replacement of ears by a standardised tissue model should be carried out to enhance inter-comparability of results, which is limited by the high variability of shape and low shelf life of the ears. The results of the present study indicate the high complexity of this task and show a demand for extensive studies with different shapes and types of materials and a variety of different transponder ear tags.

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CHAPTER 3

MONITORING TROUGH VISITS OF GROWING-FINISHING PIGS WITH UHF-RFID

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Monitoring trough visits of growing-finishing pigs with UHF-RFID

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ABSTRACT

Automatic monitoring of animal feeding behaviour in commercial farms is desirable as it is an important indicator for the well-being and health of animals. Low-frequency and high-frequency radio frequency identification (RFID) systems have been tested for the detection of feeding visits of growing-finishing pigs, but the suitability of ultra-high frequency (UHF) RFID for this application has not yet been shown. Therefore, the objective of this study was the validation of a UHF-RFID system, consisting of a reader, antennas and passive transponder ear tags, for the monitoring of visits of growing-finishing pigs at a short trough for liquid feeding. Consequently, (1) two antenna variants (free-form and patch antennas) were tested at different levels of antenna output power, (2) two methods to determine a bout criterion for the creation of trough visits from the RFID registrations were compared, and (3) a comparison of the RFID data with reference data from video observation was carried out. The analysis showed that the reading area exceeded the trough especially in the variants with high output power. Thus, the evaluation of the first and second rate of change of the total daily number and total daily duration of visits led to higher values for the bout criterion (50 s for both antenna variants) than the evaluation of the mean absolute deviation between video and RFID data (20 s for the free-form antenna and 30 s for the patch antennas). The trough visits observed were detected best with the patch antennas at 25 dBm output power and a bout criterion of 30 s with regard to average precision (61.1%), and correlation between the video data and RFID visits ($R^2 = 0.87$ for total number and 0.80 for total duration of visits). The average sensitivity of this variant was 49.7%, specificity 99.0% and accuracy 97.9%. The highest average sensitivity (79.7%) and a good correlation between video data and RFID visits ($R^2 = 0.78$ for total number, 0.56 for total duration of visits with a bout criterion of 50 s) were measured with the free-form antenna at 26 dBm. In conclusion, UHF-RFID can be suitable for the monitoring of trough visits of growing-finishing pigs, but the effect of ear tissue on the performance of the UHF-RFID ear tags should be reduced by further development. In addition, further research should be carried out to evaluate the potential of this technology completely for animal behaviour monitoring.

1. Introduction

Activity and behaviour measurements in livestock are important not only for scientific purposes, but also in precision livestock farming (PLF) systems, using them as input variables for control and management processes (Berckmans, 2008). Feeding behaviour is one of the most important indicators for the well-being and health of animals (Hart, 1988; Weary et al., 2009). Proof of this has been given for different diseases and animal species. González et al. (2008), for example, detected a decrease of daily feed intake, feeding time and feeding rate of dairy cows with ketosis in average 3.6 days before animal care takers observed the disease. Brown-Brandl et al. (2013) measured a significant decrease in the daily time growing-finishing pigs with pneumonia spent at the feeder. Feeding behaviour can also reflect the response of an animal to its environment (Averós et al., 2012). Influencing factors can be, for example, air temperature (Feddes et al., 1989), temperature humidity index (Brown-Brandl and Eigenberg, 2015) and type of feeder as well as feeder space allowance (Brumm et al., 2000; Gonyou and Lou, 2000). The connection of social behaviour and social constraints like degree of competition (Georgsson and Svendsen, 2002) and social rank (Cornou et al., 2008) to feeding behaviour has also been described. Automatic monitoring systems have been gaining in importance as they allow for continuous data acquisition and are less time consuming compared to direct or video observations. Many of these systems are used in single-space feeders that already make individual feed intake measurements possible (Chapinal et al., 2007; Hoy et al., 2012; Junge et al., 2012; Chizzotti et al., 2015). However, to collect feeding behaviour data on a larger scale for use in PLF systems, monitoring devices

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that can be used on-farm in commercial feeders for multiple animals and which do not interfere with the normal feeding behaviour in these facilities have to be developed. Two approaches have been shown in literature. Brown-Brandl and Eigenberg (2011) developed a feeding behaviour monitoring system based on low-frequency radio frequency identification (LF-RFID, 134.2 kHz) for use in feed-lot cattle and growing-finishing pigs. This system used multiple reader antennas and multiplexers to enable the detection of multiple animals at a time. Each antenna was placed at a single feeding space in feed bunks (cattle) and five-space dry feeders (pigs). The authors used standard passive electronic ear tags for animal identification. Maselyne et al. (2014) applied a high-frequency RFID (HF-RFID, 13.52 MHz) system to detect growing-finishing pigs at a round trough. Only one antenna was used here for each trough, applying the ability of HF-RFID systems to detect several transponders quasi-simultaneously by use of anti-collision algorithms. Hereby, feeder visits of multiple pigs feeding at the same time could be detected. Standard button ear tags with a passive disk transponder applied as an inlay on the pin of the male part of the ear tag were used in these experiments. While LF-RFID is a standard in animal identification (ISO 11784 and ISO 11785), HF-RFID has so far only been used for scientific purposes in this field of application (Reiners et al., 2009; Thurner et al., 2010). The third important RFID frequency band, ultra-high frequency (UHF, 860–960 MHz), has also been tested for application in livestock in recent years (Stekeler et al., 2011; Hogewerf et al., 2013; Adrion et al., 2015c; Hammer et al., 2015, 2016). Main advantages of this technology are the flexibly adjustable read range of more than 3 m with passive transponders as well as the ability to detect a high number of transponders per second by utilizing the high speed of communication (Ruiz-Garcia and Lunadei, 2011; Finkenzeller, 2012). These properties could facilitate various applications of UHF-RFID in animal behaviour monitoring. However, there is a negative influence of materials, in this case ear tissue, on the performance of UHF RFID transponder ear tags, mainly through absorption of radiation and a change in the resonance frequency of the transponder. This has inhibited the application of this technology in animal husbandry until a few years ago and has to be thoroughly taken into account for the development of UHF-RFID ear tags (Lorenzo et al., 2011; Adrion et al., 2015b). Applications of UHF-RFID already tested were mainly single animal identification and group identification for traceability purposes (Baadsgaard, 2012; Hogewerf et al., 2013; Pugh, 2013; Hammer et al., 2016), but activity and behaviour monitoring of individual animals in group settings with passive UHF-RFID has not yet been reported in literature.

1.1. Objectives

The experiments shown here were part of a joint research project concerned with the development of UHF-RFID ear tags for use in pigs and cattle, as well as readers and antennas for on-farm use (Federal Office for Agriculture and Food, 2012). The objective of this study was the validation of a UHF-RFID system, consisting of a reader, antennas and passive transponder ear tags, for monitoring of visits of growing-finishing pigs at a short trough for liquid feeding. To achieve this, the main tasks were (1) to test two antenna variants at different levels of antenna output power, (2) to compare two methods to determine a bout criterion for the creation of trough visits from the RFID registrations (raw data), and (3) to compare raw data and trough visits at different levels of output power with reference data from video observation to determine critical points for further development of the UHF-RFID system.

2. Materials and methods

2.1. Animals and test facility

The experiments were conducted in a growing-finishing pig barn at the Agricultural Sciences Experimental Station of the University of Hohenheim between February 4 and 16 (day 1–13), 2015. The experimental pen observed had a total size of approximately 3.30 m × 7.80 m and held 25 pigs (approximately 0.95 m^2 per animal). These pigs (10 male, 15 female) had an average weight of 110.4 ± 10.6 kg (mean ± standard deviation: SD) at the start of the experiment. Nine of the 25 pigs were sold to the slaughterhouse on day 9, increasing the space per pig to approximately 1.5 m^2. The pen was equipped with a slatted floor in the defecation area and the other two-thirds of the pen had a slatted floor with reduced perforation, functioning as a lying and feeding area. The feeding of the pigs was carried out with a sensor-controlled liquid feeding system at a metal short trough (1.50 m × 0.37 m, five feeding spaces of 30 cm each). The animal to feeding place ratio was 6:1 from day 1–9, and 4:1 for the rest of the experiment. However, from day 9 on all feeding spaces of the trough were still occupied during the main feeding times as before day 9, ensuring comparable conditions for the registration of the pigs during feeding. Feed was given at six feeding times, split into two meals each (6:00, 6:20, 9:00, 9:20, 12:00, 12:20, 15:00, 15:20, 18:00, 18:50, 21:40 and 22:00). Seven of these 12 meals were included in the daily monitoring time of this experiment from 11:00 to 22:00. On day 7 the meals at 15:00 and 15:20 were left out due to technical problems with the feeding system, but the data acquisition went on during this time. There were three additional nipple drinkers on the opposite side of the pen. A playing device, which consisted of a straw-filled metal container with a trough and a free-hanging wooden beam, was placed on the long side of the pen in the fully slatted area.

Eight focal pigs were chosen out of the 25 pigs (genetics: German Landrace x Pietrain, sex: 7 females, 1 male) with an average weight of 99.9 ± 8.3 kg (mean ± SD) at the beginning of the test period. They were tagged with UHF transponder ear tags in the right ear. No larger number of ear tags was available for this experiment due to the complexity of the ear tag production at this phase of the project. The eight animals were marked individually with colour for video observation and the ear tags were checked with a handheld reader and visually for signs of damage on each test day. Two ear tags lost their function during the experiment (on day 7 and day 11). These two ear tags showed signs of biting already several days before they stopped working and also much less readings of these tags could be detected during that time. The exact time of the first damage could not be determined exactly, thus, these two animals were completely excluded from the data analysis.

The experimental procedures were approved by the regional authorities in Baden-Württemberg, Germany, and were carried out in accordance with EU Directive 2010/63/EU for animal experiments.

2.2. UHF-RFID system

The transponders used had a planar inverted F-shaped antenna design (Fujimoto and Morishita, 2013) and were equipped with an Impinj Monza 4® chip. The transponder antenna was made of a copper layer on polyimide foil. The outer dimensions of the transponders, approximately 30 mm × 40 mm, were shaped to fit into a pig ear tag, but they were grouted into the female part of a cattle ear tag (Primaflex®, Caisley International GmbH, Bocholt, Germany) because only an injection mold for cattle ear tags was available at this stage of the project (Fig. 1).

Two reader antenna variants were tested for monitoring the feed trough. The first one was a Locfield® free-form antenna (Cavea Identification GmbH, Olching, Germany). It had a total length of 3 m with an active part of 2 m. This type of antenna is made of a coaxial cable (diameter 5 mm, attenuation 0.28 dBm/m at 800 MHz). The antenna was mounted parallel to and approximately 0.1 m above the back side of the trough (Fig. 2). The antenna was shielded by plastic pipe (32 mm outer diameter, 27 mm inner diameter, PVC) to protect it from water, dirt and biting of the pigs. The field strength of this antenna

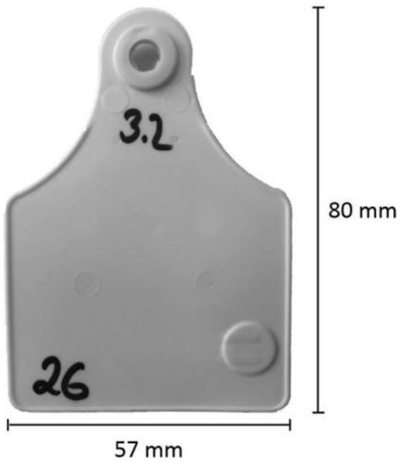

Fig. 1. UHF transponder ear tag used in the experiment.

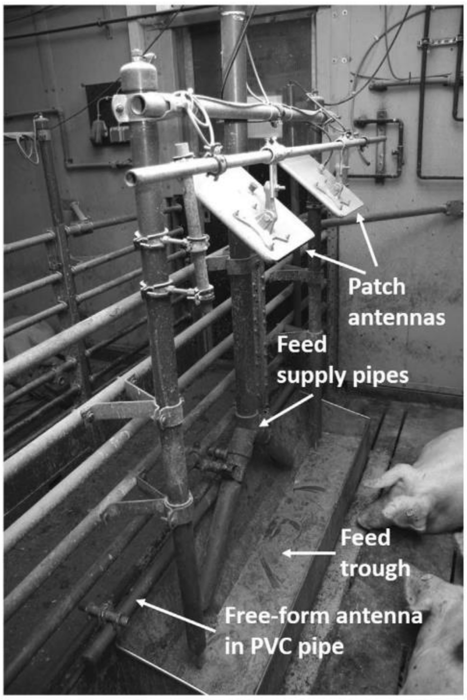

Fig. 2. Feed trough with feed supply pipes, patch antennas and free-form antenna in a PVC pipe.

slightly decreases from the tip to the base. To increase the field strength at the end of the trough with the aim of creating an evenly distributed antenna field, the remaining 0.5 m of the antenna's active part at the end of the trough was bent at a 90° angle and led upwards towards the reader. The second antenna variant consisted of two patch antennas (MT-242014/NRH/K, MTI Wireless Edge Ltd., Rosh-Ha'Ayin, Israel) that were positioned above the trough (Fig. 2). The centre of each antenna was positioned 0.45 m distant from the short side of the trough, 0.25 m distant from the pen partitions and 1.32 m above the floor. This antenna type has a symmetrical opening angle of 65°, a gain of 3.4 dBd and provides circular polarised radiation. Pretests (data not shown) had revealed that the antenna field reached too far into the pen when the patch antennas were mounted horizontally. For this reason, the antennas were mounted at an angle of 40° towards the pen partitions in the current experiment.

The reader used was a functional model developed within the research project (deister electronic GmbH, Barsinghausen, Germany and Agrident GmbH, Barsinghausen, Germany) with a multiplexer for four antennas. The operation frequency was 865.7 MHz and the maximum output power 29 dBm (0.8 W). The communication between reader and transponder followed EPC class 1, generation 2, specifications defined by ISO 18000-6C (GS1 EPCglobal Inc., 2013). Each of the antennas was turned on for 250 ms per s before switching to the next antenna port in the multiplexing process. An average of two readings per transponder and antenna could occur during one multiplexing round. The reader was connected to the antennas by a 5-m low-loss coaxial cable (attenuation 0.29 dBm/m). Antenna gain and cable loss were considered by the reader firmware for the setting of the output power. Regarding this, a maximum output power for the free-form antenna of 26.6 dBm (loss in the antenna included) and 30.9 dBm for each of the patch antennas (antenna gain included) could be reached.

2.3. Experimental procedure and data acquisition

The experiment was split into two parts to test both antenna variants (Table 1). The animals were marked with colour and the ear tags were checked for correct function each morning. The area of the trough itself was defined as the target area for the detection of the pigs. Starting output power values were determined by manual tests with an ear tag in the barn. Power settings ± 1 dBm (free-form antenna) and ± 2 dBm (patch antennas) above and below this value were also tested with the aim of adjusting the reading area for detection of the pigs only when they were at the trough (see also section on video data for exact definition of a pig's visit). A smaller power range was chosen for the free-form antenna due to pretests indicating a strong decrease of the detection area at lower output powers. One power setting was tested per day. The settings were ordered randomly and repeated twice per antenna variant (Table 1).

Relevant parameters of the tests, such as antenna position and orientation, test animals with transponder number, and output power of the antennas, were specified in a custom-made configuration software programme and stored in a database. Another software application transferred the settings defined to the reader and collected the transponder readings during the tests (Phenobyte GmbH & Co. KG, Ludwigsburg, Germany). These were stored in the same database together with the test parameters for further processing. Video observations were made daily with an IP camera (LogiLink® WC0016, 2direct GmbH, Schalksmühle, Germany) mounted on the wall opposite to the trough during the recording time. Video and RFID data were

Table 1
Overview of the test days, antenna output power and daily recording times.

Antenna variant	Test day	Output power	Recording time	Comment
Free-form	1	26	–	Technical preparations
	2	26	11:00–22:00	
	3	24	11:00–22:00	
	4	25	11:00–22:00	
	5	26	11:00–22:00	
	6	25	11:00–22:00	
	7	24	11:00–22:00	
Patch	8	23	11:00–22:00	Data discarded (antenna failure)
	9	27	11:00–22:00	
	10	25	11:45–22:00	
	11	27	11:00–22:00	
	12	23	11:00–22:00	
	13	25	11:00–22:00	

synchronised by recording on the same computer.

2.4. Data analysis

2.4.1. Video data

Video analysis was carried out by two people who equalised their scoring procedure repeatedly. Continuous scoring was carried out on all test days with the software Interact® 14.0 (Mangold International GmbH, Arnstorf, Germany). A focal pig was scored as "in the target area" when its complete head, including both ears, was above or inside the trough. Start and end time were recorded for each visiting event. It was not determined whether the pig was actually feeding during this time. It is important to mention that the RFID system could only determine whether a pig was in the reading area of one of the antennas, but could not distinguish between random visits and actual feeding events. Because of this, all visits at the trough in video and RFID data are called "trough visits" and not "feeding visits" in this article. The visits recorded by video analysis were taken as reference data for the validation of the RFID system.

2.4.2. Creation of trough visits using visit criteria

The RFID registrations (commonly called readings) of an ear tag do not normally appear at regular intervals. The UHF transponders are especially sensitive to the influence of materials, in this case ear tissue, in their immediate vicinity (Griffin et al., 2006; Lorenzo et al., 2011). Interference due to reflections of the antenna radiation in the reading environment can also lead to a lower reading rate in certain areas (Griffin and Durgin, 2009). These factors lead to random reading gaps when a pig is moving its head while in an area of the antenna field in which the transponder would normally be registered. Trough visits were created from the RFID raw data using visit criteria, as has been shown before by several authors (Hessel and Van den Weghe, 2013; Adrion et al., 2015a; Brown-Brandl and Eigenberg, 2015; Maselyne et al., 2016), to close these gaps and herby optimise the congruence of RFID and video observation data.

A bout criterion and a minimum duration criterion were applied. Different values for the minimum duration criterion of a trough visit were tested together with a bout criterion of 20 s in a pre-analysis of days 2, 7, 10 and 11. The results showed that increasing the minimum duration up to 10 s not only increased the precision very little, but also decreased sensitivity approximately the same amount or even more. On three of these four days, precision at maximum increased 0.4%, and increased 1% only on day 11 with a minimum duration criterion of 10 s. However, sensitivity also decreased 1% on that day, and between 1.3% and 1.9% on the other three days. Because of this minimal positive effect on precision and a stronger negative effect on sensitivity, the minimum duration was kept to 1 s throughout this study to erase random registrations of pigs just passing the reading area very quickly. Hence, the focus of the analyses of this study lay on finding an optimum bout criterion to create trough visits.

Two different approaches were tested and compared to find the optimum bout criterion. Brown-Brandl and Eigenberg (2015) estimated the minimum meal interval for feeding data collected by an LF-RFID system in feed bunks for feed-lot cattle by determining the inflection point of the graphs of daily number of meals (TNUM), total daily feeding duration (TDUR) and average meal length (ADUR) over increasing minimum meal intervals. The authors calculated the first and second rate of change of these graphs by interval differencing. The optimum minimum meal interval was assumed to be at the minimum of the first derivative, meaning that the rate of change of the original graph was minimal. This bout criterion was verified by determining the point where the second derivative was equal to zero. At this bout criterion, many artificial and short visits should be merged, while the data is not aggregated too much (Zorrilla et al., 2005; Brown-Brandl and Eigenberg, 2015). This approach was applied on the RFID raw data in the current study, assuming that a similar course of the graphs will occur for aggregation of single RFID registrations to trough visits as they did for aggregation of trough visits to meals in the study of Brown-Brandl and Eigenberg (2015). Therefore, in the current analysis, the first and second rate of change of the mean TNUM, TDUR and ADUR of all six focal animals during the daily recording time were calculated with varying bout criterion (5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 s). The point where the graphs of the second rate of change approached zero was determined graphically and chosen as the bout criterion to create trough visits.

The second method applied to estimate the optimum bout criterion was by comparing the TNUM and TDUR of the RFID data to the TNUM and TDUR of the video data, similar to Maselyne et al. (2016). The bout criterion leading to the least difference in these parameters between observed and video data should be chosen as the optimum criterion. Consequently, the mean values of the absolute percentage deviation of the TNUM and TDUR of the RFID data from the video data of all six focal animals were calculated for each test day. In the next step, the average of these two means was calculated, resulting in the combined mean absolute deviation of the TNUM and TDUR of each test day. Finally, the bout criterion with the smallest value of this mean deviation was chosen for the analysis. The two bout criteria were compared afterwards in terms of performance of the RFID system and congruence with the video data.

2.4.3. Calculation of performance measures of the RFID system

Performance measures of the raw RFID data as well as the RFID events created were calculated with reference to Maselyne et al. (2016). Calculations were carried out to the split second for the whole recording time of each test day, for all focal animals together and individually with a self-developed Visual Basic for Applications Macro in Excel 2016 (Microsoft Corporation, Redmond, WA, USA). The following definitions were made.

- P = number of positives: s during which a focal pig was observed in the target area.
- N = number of negatives: s during which a focal pig was not observed in the target area.
- TP = number of true positives: positives during which an RFID registration (raw data) of the same pig occurred or which were part of an RFID event of this pig.
- FP = number of false positives: negatives during which an RFID registration (raw data) of the same pig occurred or which were part of an RFID event of this pig.
- TN = number of true negatives: negatives during which no RFID registration (raw data) of the same pig occurred or which were not part of an RFID event of this pig.
- FN = number of false negatives: positives during which no RFID registration (raw data) of the same pig occurred or which were not part of an RFID event of this pig.

Sensitivity, specificity, accuracy and precision were calculated on the basis of these definitions and the following formulae:

$$Sensitivity\ [\%] = \frac{TP}{P} \times 100$$

$$Specificity\ [\%] = \frac{TN}{N} \times 100$$

$$Accuracy\ [\%] = \frac{(TP + TN)}{(P + N)} \times 100$$

$$Precision\ [\%] = \frac{TP}{(TP + FP)} \times 100$$

The registrations of all focal pigs of each test day were analysed together, giving one value for each performance measure on each test day, for the investigation of the raw data. The mean and SD of the performance measures were calculated from the results of all focal pigs on both test days of each variant tested (two data points per focal pig and variant) in the analysis of the RFID visits. This resulted in one value per combination of antenna variant and output power.

2.4.4. Correlation between video and RFID parameters

In addition to the performance measures described, the coefficients of determination (R^2) of linear regressions of the TNUM and TDUR from the RFID visits against the corresponding values of the video data were calculated. Moreover, the coefficients of determination were calculated for regressions of the number of RFID registrations in the raw data against the TDUR of the video data. This analysis was carried out by combining the results of all focal pigs on the two test days for each combination of antenna variant and output power (two data points per focal pig and variant). The regressions were computed with OriginPro 2016G (OriginLab Corporation, Northampton, MA, USA) and the regression coefficients were tested for significance ($p < .05$).

3. Results and discussion

3.1. Video data

An overview of the daily number (TNUM) and duration (TDUR) of trough visits on the test days observed by video is given in Table 2. An average of 158 ± 41 (mean ± SD) trough visits was observed on each test day with a mean TDUR of 91 ± 32 min. The mean TDUR per pig was 15 ± 5 min. It varied between 8 ± 5 and 25 ± 9 min. The focal animals by tendency stayed longer at the trough on the last three days than on all other test days.

The trough visits of the pigs were mostly connected to the feeding times of the sensor-controlled liquid feeding system. The trough was nearly empty after most of the meals, because the system was feeding near the saturation level of the pigs and lowered the amount of feed dispensed when the pigs emptied the trough too slowly. This and the relatively high level of competition for feed in this system explains the relatively short TDUR measured compared to literature. Using a similar feeding system, but a different feeding regime, Rasmussen et al. (2006) measured an average TDUR of 41.7 min per day (24 h) in 17-week-old pigs. Maselyne et al. (2014) observed an average TDUR of 29 ± 14 min of pigs with an average weight of 40.2 kg at a round trough with ad libitum dry feed in 11.5 h of observation per day, and Brown-Brandl et al. (2013) recorded an average feeding duration at an ad libitum dry feeder of 76.7 min per day (24 h) in finishing pigs above 107 days of age. In conclusion, an average feeding time of 15 min per pig is relatively low, even though the sensor controlled liquid feeding system is a restricted feeding system regarding the feeding times and only seven out of twelve feed dispersions per day were observed here.

Table 2
Daily sum and mean ± SD of total daily number (TNUM), duration (TDUR) and average duration (ADUR) of the trough visits (video data) of the focal pigs observed on all test days.

Daily sum of all focal pigs			Mean ± SD per focal pig and day		
Test day	TNUM	TDUR [min]	TNUM	TDUR [min]	ADUR [s]
2	114	69	19 ± 11	11 ± 3	58 ± 60
3	115	47	19 ± 10	8 ± 5	34 ± 31
4	183	68	31 ± 30	11 ± 6	45 ± 39
5	179	74	30 ± 18	12 ± 4	31 ± 15
6	114	68	19 ± 9	11 ± 7	39 ± 18
7	150	94	25 ± 10	16 ± 4	45 ± 24
9	203	91	34 ± 21	15 ± 6	31 ± 10
10	93	88	16 ± 13	15 ± 7	69 ± 27
11	196	151	33 ± 16	25 ± 9	50 ± 14
12	191	142	32 ± 16	24 ± 8	54 ± 28
13	197	112	33 ± 17	19 ± 7	38 ± 10

The video observations showed that the behaviour of the focal animals changed between the test days. Consequently, the data basis for the evaluation of the UHF-RFID system was not the same on all days, which should be kept in mind when assessing the results of the validation. The last three days, especially, differed from the other days. By tendency, the pigs spent more time at the feeder because of a lower animal to feeding place ratio after some pigs had left the group a day before.

3.2. RFID raw data

All trough visits of all focal animals on a test day were analysed together for the analysis of the RFID raw data (Table 3). The highest sensitivity was achieved at the highest antenna output power tested. An average of 38.4% was reached for the free-form antenna at 26 dBm and 33.2% for the patch antennas at 27 dBm. Specificity was above 99% and accuracy was above 96% on all days. However, precision was around 50% on most of the days, indicating that approximately half of the RFID registrations in all variants were recorded outside of a visit of the pigs observed by video.

A low sensitivity was expected for the RFID raw data, because RFID registrations do not generally occur continuously, but with an irregular interval between single registrations. This produces time gaps that lower sensitivity. To close these gaps, the creation of visits from the single registrations is necessary, as described in Section 2.4.2. The results obtained here are comparable to those presented by Maselyne et al. (2016) for the registrations of fattening pigs using a HF-RFID system at a round trough. The authors measured an average sensitivity of 17.6%, specificity of 99.6%, accuracy of 93.9%, and precision of 73.8% with the RFID registrations. The high specificity and high accuracy in both studies can be explained by the high number of s when the pigs did not visit the trough (here: ~230,000 s of absence from the trough per day for 6 focal pigs compared to ~5000 s of visits per day). In comparison to that, the number of false positives was relatively low on all days.

Nevertheless, low values of precision around 50% on days with high output power indicate that approximately half of all RFID registrations were false positive, meaning that they occurred before or after a trough visit. However, also on days with lower output power precision was not much higher. Since the number of false positives will not be reduced by creating visits from the raw data, but will be increased, precision can only be improved in the variants with a higher number of true positives. Thus, the days with the highest output power tested (free-form antenna 26 dBm, patch antennas 27 dBm) were chosen for further analyses because of the higher sensitivity. The days with a power level 2 dBm below the highest value (free-form antenna 24 dBm, patch antennas 25 dBm) were also converted into visits and analysed in terms of performance to investigate the precision of the RFID data at a lower power level.

3.3. Determination of an optimum bout criterion

As explained previously, the minimum duration criterion was set to 1 s in all cases in the following analyses. In the first step, an optimum bout criterion was estimated according to Brown-Brandl and Eigenberg (2015) (see Section 2.4.2). Therefore, the changes in average TNUM, TDUR and ADUR of all focal animals were investigated by plotting them against the bout criterion and calculating their first and second rate of change. As an example, the data of all four days with the highest output power (free-form antenna 26 dBm, patch antennas 27 dBm) is shown in Fig. 3. The analysis of day 3 and 7 (free-form antenna 24 dBm) and 10 and 13 (patch antennas 25 dBm) yielded very similar results (not shown).

The smoothest graphs were obtained for the average TNUM. The curves decreased steadily and stabilised on a certain level. In contrast to that, both average TDUR and ADUR did not increase that uniformly and

Table 3
Sensitivity, specificity, accuracy and precision of the RFID raw data for both antenna variants (free-form and patch antennas) with differing output power level. Values calculated from all trough visits of all focal pigs on each test day.

Antenna variant	Output power [dBm]	Test day	Sensitivity [%]	Specificity [%]	Accuracy [%]	Precision [%]
Free-form	24	3	24.1	99.6	98.7	43.7
	24	7	27.7	99.7	98.0	67.7
	25	4	39.2	99.5	98.5	58.1
	25	6	31.9	99.5	98.3	50.8
	26	2	40.2	99.4	98.3	53.2
	26	5	36.5	99.3	98.1	49.4
Patch	23	12	10.9	99.9	96.8	88.0
	25	10	20.7	99.4	97.5	46.3
	25	13	21.0	99.7	97.5	68.8
	27	9	32.3	99.3	97.7	51.4
	27	11	34.0	99.0	96.5	56.5

did not reach a clear plateau. The average ADUR showed similar curves to the TDUR, but no clear approach of a plateau was visible in the first and second rate of change. A few outliers in ADUR occurred, for example, on day 5, with a bout criterion of 110 s. At these points, several visits of one pig were joined to one large visit, very strongly increasing the average ADUR of the respective day.

The influence of the bout criterion shows, for example, the data of day 11, where the average TNUM decreased from 89.3 visits per pig and day with a bout criterion of 5 s to 16.7 with a bout criterion of 120 s, while the average TDUR increased from 1088 (18 min) to 3190 s (53 min) and the average ADUR from 12 s to 200 s in parallel. This method resulted in a bout criterion between 40 and 60 s for all 8 days analysed, only for day 13, 30 s were already sufficient. The average of all results was 50 s. This value was chosen as the bout criterion for all days. At this point, the second rate of change of all TNUM graphs was near zero (below 0.07) and the second rate of change of the TDUR, in

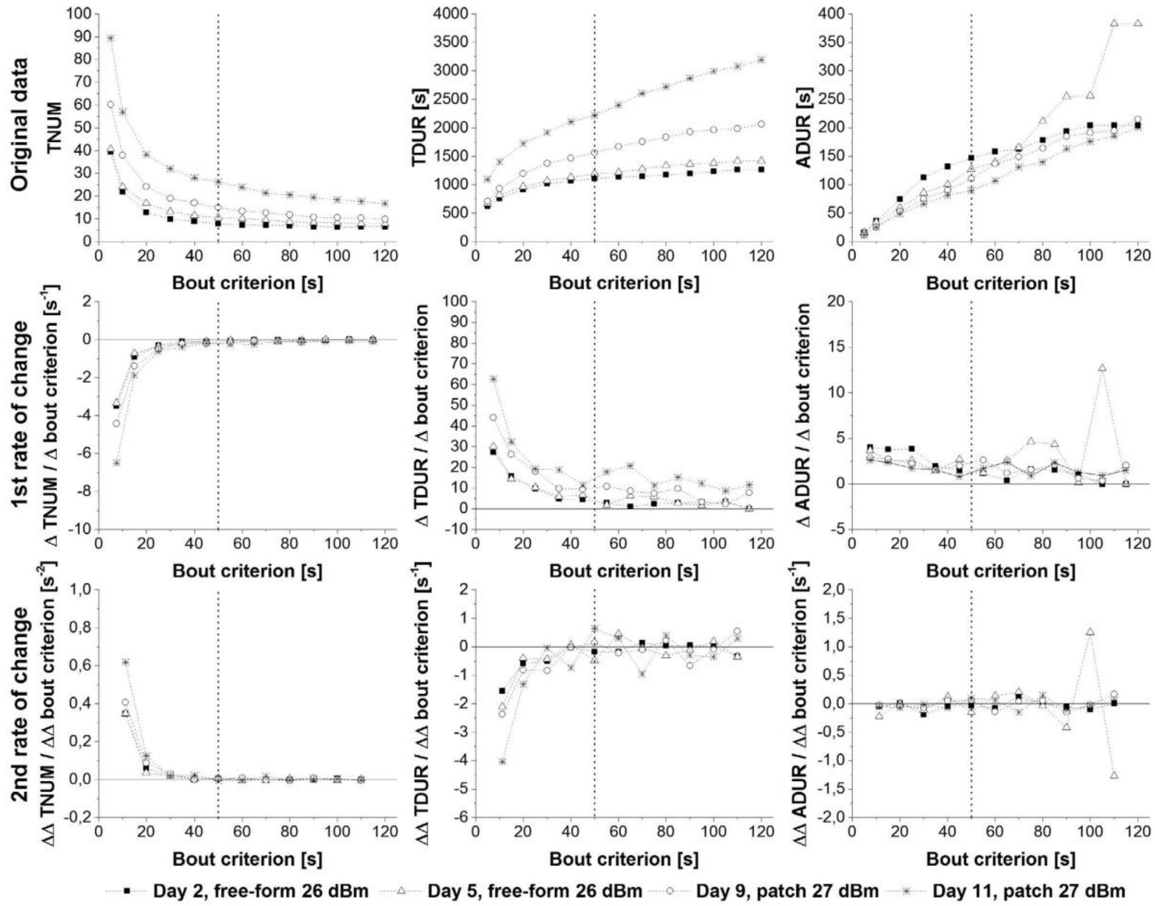

Fig. 3. Estimation of optimum bout criterion by interval differencing. Average total daily number (TNUM), total daily duration (TDUR), and average duration (ADUR) per focal pig and their first and second rates of change on day 2 and 5 (free-form antenna, 26 dBm) and day 9 and 11 (patch antennas, 27 dBm) against increasing bout criterion. Dashed vertical line: chosen bout criterion 50 s.

Table 4
Optimum bout criterion after evaluation of the mean absolute deviation between RFID visits and video data. Mean absolute deviation was calculated as the combined average of the absolute mean deviation of all focal pigs in total daily number (TNUM) and total daily duration (TDUR) of each test day.

Antenna variant	Output power [dBm]	Test day	Min. duration [s]/ bout criterion [s]	Mean deviation [%]
Free-form	26	2	1/20	38.1
		5		40.6
	24	3		63.6
		7		26.2
Patch	27	9	1/30	42.1
		11		33.1
	25	10		31.0
		13		34.6

most cases, varied slightly less from 50 s upwards. Because the graphs did not reach a plateau, the ADUR was not considered for the estimation of the bout criterion.

In a second approach, on the basis of Maselyne et al. (2016), the mean deviation in the TNUM and TDUR between the RFID visits and the visits observed was calculated to find a bout criterion that produced the smallest differences between RFID and video data (see Section 2.4.2). Table 4 shows the mean deviation for the optimum bout criterion. A bout criterion of 20 s was determined for the free-form antenna and 30 s fitted best for the patch antennas. However, the chosen criterion was not optimal for one day of both antenna variants. On day 5, a bout criterion of 10 s would have produced a mean absolute deviation of 28.9% and for day 9, a bout criterion of 20 s would have resulted in a mean absolute deviation of 32.4%. Nevertheless, the same bout criterion was chosen for all days of an antenna variant to conduct a uniform analysis. This resulted in an average of the mean absolute deviation of 42.1% for the free-form antenna and 35.2% for the patch antennas.

The trough visits of all focal pigs in 1 h of day 2 are shown in Fig. 4 to illustrate the effect of the visit creation on the RFID raw data. It is clearly visible that the main visits of the pigs were all detected by the UHF free-form antenna, but it is also obvious that several RFID visits were registered after or before an observed visit or even when no visit was detected on the video. For these events, it was investigated on the video what the respective pigs did. Pig 1 (~15:33–15:34), Pig 3 (~15:44–15:45) and Pig 4 (~15:36–15:41) were biting on the tip of the PVC tube protecting the free-form antenna or licking spilled feed from the floor next to the trough. Pig 2 (~15:10–15:12) was standing directly to the right of the trough, trying to get a feeding space at the occupied trough, and Pig 3 (~15:46–15:50) was lying next to the trough with its right ear and the UHF ear tag inside the trough.

The two methods applied for the creation of visits from the RFID raw data led to different results. A higher bout criterion was estimated with the method shown by Brown-Brandl and Eigenberg (2015), and lower bout criteria were chosen following the evaluation of the mean absolute deviation between RFID visits and observed visits following Maselyne et al. (2016). These methods have never been compared before. Therefore, it is necessary to find out if one of the two methods is more appropriate than the other and why they led to different results.

The main difference between the two methods is that the first one estimates an inherent criterion of the RFID data, while the second method is only oriented towards the video data. Fig. 4 illustrates that the bout criterion of 50 s found with the method by Brown-Brandl and Eigenberg (2015) aggregated the main visits detected by the RFID system very well. However, the bout criterion of 20 s led naturally to less overestimation of TDUR, thus, it fitted the video data better. Indeed, a bout criterion of 5 s would have been optimal for the data of this day when looking only at the mean absolute deviation of TDUR (23.3%) and not at the mean absolute deviation of TNUM (212.0%). Independent of both methods, even the RFID raw data produced many false positives in this example and on all other test days, as Fig. 4 and Table 3 and the high deviation between RFID and video data (Table 4) show. The examples shown above illustrate that some visits of the pigs next to the trough were also registered by the UHF system. With the higher bout criterion, all readings, including these false positives, were aggregated to longer visits representing the presence of the focal pigs in the reading area, but not in the target detection area.

A clear recommendation for one or the other method for estimation of a bout criterion cannot be given. It might be preferable to use the method of Brown-Brandl and Eigenberg (2015) when the registration area cannot be adjusted well, because this would, at least, aggregate the registrations obtained well, independently of the deviation from the target area. For example, at locations that are rectangular, such as the trough monitored in this study, the antenna field and thus the registration area will never match the target area perfectly, so that this method could be applied. However, if such a situation occurs and the

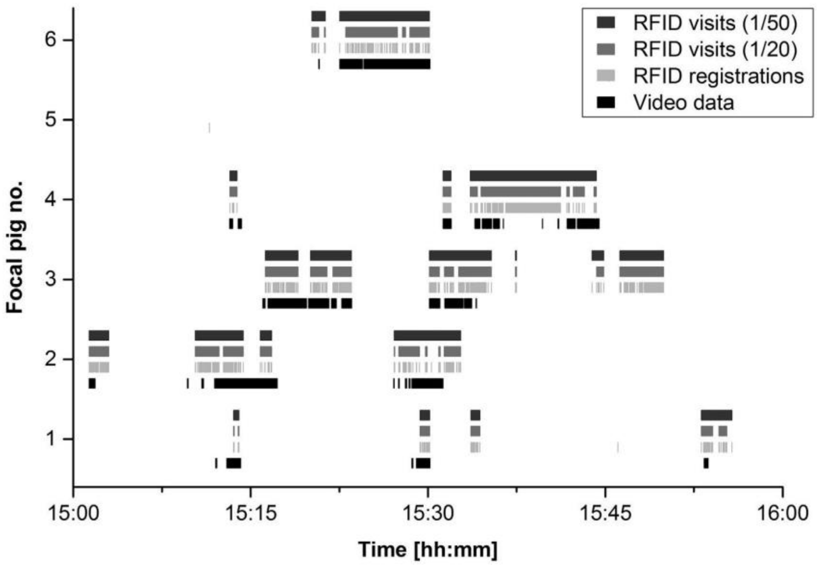

Fig. 4. Trough visits of the six focal pigs on day 2 between 15:00 and 16:00 (free-form antenna 26 dBm). Video data is shown in combination with RFID raw data (registrations) and RFID visits with a minimum duration criterion of 1 s and a bout criterion of 20 s or 50 s.

Table 5

Mean ± SD of sensitivity, specificity, accuracy and precision of the RFID visits calculated with a bout criterion of 20 s for the free-form antenna, 30 s for the patch antennas and 50 s for both antenna variants with different output power levels (values per pig and day for both test days of each variant).

Antenna variant	Output power [dBm]	Min. duration [s]/ Bout criterion [s]	Sensitivity [%]	Specificity [%]	Accuracy [%]	Precision [%]
Free-form	26	1/20	68.6 ± 15.0	98.8 ± 0.8	98.3 ± 1.0	56.6 ± 20.2
		1/50	79.7 ± 13.5	98.5 ± 1.0	98.2 ± 1.1	54.9 ± 20.2
	24	1/20	56.3 ± 18.3	99.3 ± 0.5	98.5 ± 0.6	59.4 ± 25.7
		1/50	72.8 ± 19.0	98.8 ± 0.9	98.3 ± 0.8	56.4 ± 26.2
Patch	27	1/30	70.6 ± 14.5	98.0 ± 1.5	97.2 ± 1.6	55.6 ± 20.0
		1/50	78.3 ± 14.6	97.6 ± 1.7	97.1 ± 1.8	53.8 ± 19.0
	25	1/30	49.7 ± 24.5	99.0 ± 1.3	97.9 ± 1.6	61.1 ± 27.2
		1/50	57.9 ± 28.1	98.8 ± 1.5	97.9 ± 1.7	60.3 ± 26.8

sensitivity, specificity and/or precision of the system are not satisfying, it should be proven that the TNUM and TDUR of the RFID system are well correlated with TNUM and TDUR of the observed visits or registrations. Thus, at least the total daily number and duration of the visits could be estimated with such a system. In the following section the performance of the trough visits created with the bout criteria of both methods will be investigated in detail.

3.4. *RFID visits*

The results of the comparison between the visits observed and RFID visits show a clear pattern, depending on the bout criterion and the output power of the RFID antenna (Table 5). Both days of each antenna variant at each output power level were analysed together for this analysis. The RFID visits of each antenna variant created with a bout criterion of 50 s had a higher average sensitivity, but lower average specificity, accuracy and precision than visits created with a bout criterion of 20 or 30 s. The highest average sensitivity, but also the lowest average specificity, accuracy and precision were reached at the higher output power level tested in each antenna variant. An average maximum sensitivity of 79.7 ± 13.5% (mean ± SD) was achieved with the free-form antenna at 26 dBm and a bout criterion of 50 s, and the minimum with the patch antennas at 25 dBm and a bout criterion of 30 s (49.7 ± 24.5%). The average precision was between 55 to 61% in all cases.

In addition to the performance measures, the coefficients of determination of linear regressions of the number of RFID registrations against the TDUR of the video data as well as the TNUM and TDUR of the RFID visits against the TNUM and TDUR of the video data were also calculated. The results showed no clear pattern in connection to the output power (Table 6). The TNUM could be predicted well by the TNUM of the RFID visits for the free-form antenna at 26 dBm. Coefficients of determination of 0.76 and 0.78 were calculated here. The TDUR could not be predicted that well in this variant; the maximum R^2 was 0.66 with the RFID registrations. For the free-form antenna at an output power of 24 dBm the correlation of RFID and video data were low. Regarding the patch antennas, the results were better for the days with 25 dBm. The TNUM could be predicted with an R^2 of 0.87 by the TNUM of the RFID visits with a bout criterion of 30 s, the TDUR with an R^2 of 0.80. Similar results were gained for this variant and the visits with a bout criterion of 50 s. The coefficients of determination for the data of the patch antennas at 27 dBm were much lower. No significant regressions were found for TNUM and TDUR was predicted with a R^2 of 0.60 by TDUR of the RFID visits.

The sensitivity of both antenna variants was comparable with the sensitivity of the HF-RFID system investigated by Maselyne et al. (2016). The authors calculated a sensitivity of 68.6 ± 13.4%, also with calculations to the split second and using the data of one ear tag per pig. Reiners et al. (2009) measured an identification rate of 97.3% using an HF-RFID system for the detection of weaned piglets at a round trough, meaning that 97.3% of the trough visits observed were also detected by the RFID system. The identification rate in the current study was 84.5% for the free-form antenna at 26 dBm and RFID visits with a bout criterion of 50 s (84.5% of the video events contained at least one RFID registration). The identification rate was 71.7% for the patch antennas at 25 dBm and with a bout criterion of 50 s. Brown-Brandl and Eigenberg (2011) measured an accuracy of an LF-RFID system for detection of finishing pigs at a dry feeder of 98.8 ± 0.8% in a 12-h validation period with three pigs. This LF-RFID system could register the pigs only on a 20-s basis, therefore, a comparison with the UHF system, which allowed for approximately two registrations per second, is difficult. A higher interval of registration generally improves the agreement of video and RFID data automatically (Maselyne et al., 2016), thus, the accuracy between 97.1 and 98.5% measured with the UHF system here can be rated at least equal to the results of Brown-Brandl and Eigenberg (2011). The specificity (98.5 ± 0.8%) and accuracy

Table 6

Coefficients of determination (R^2) of linear regressions of the total daily number (TNUM) and total daily duration (TDUR) of the RFID visits calculated against the corresponding values of the video data as well as linear regression of the number of registrations (RFID raw data) against the TDUR of the video data. The RFID visits were calculated with a minimum duration criterion of 1 s and a bout criterion of 20 s (free-form antenna) and 30 s (patch antenna), and 50 s for both antenna variants. R^2 of non-significant regressions were removed from the table (n.s.).

		R^2 of regression between	RFID data				
			Raw data	RFID visits 1/20 and 1/30		RFID visits 1/50	
Antenna variant	Output power [dBm]	Video data	Number of registrations	TNUM	TDUR	TNUM	TDUR
Free-form	26	TNUM		0.76		0.78	
		TDUR	0.66		0.62		0.56
	24	TNUM		n.s.		0.46	
		TDUR	0.49		0.47		n.s.
Patch	27	TNUM		n.s.		n.s.	
		TDUR	0.43		0.60		0.60
	25	TNUM		0.87		0.84	
		TDUR	0.54		0.80		0.78

(96.4 ± 1.0%) of the system of Maselyne et al. (2016) were also at the same level as the UHF antennas investigated here, but precision was remarkably higher (76.7 ± 7.6%). Consequently, fewer false positives in relation to the number of true positives were recorded in that study.

This points out that one of the key issues for the set-up of an RFID monitoring system is the exact adjustment of the reading area of the antenna–transponder combination to the target monitoring areas. In the experiment shown here, the reading area in both antenna variants on all test days exceeded the trough a little (but in varying degrees), therefore, a focal pig could be registered when it was near the trough. This problem could be solved, at least partly, by using two ear tags per pig, as Maselyne et al. (2016) did. In their study, sensitivity increased by approximately 15% when using the data of two tags instead of one. Because of the higher identification reliability of two ear tags, this would facilitate the use of a smaller reading area to lower the number of false positives. However, it is unlikely that farmers will pay the costs of more than one electronic ear tag per animal, thus, it would be preferable to optimise the registration of one ear tag. The limitation of the reading area using UHF-RFID is more difficult than when using LF- or HF-RFID because of the fluctuating influence of the ear tissue on the transponders. In certain cases, depending on transponder antenna design, resonance frequency and location of contact between transponder antenna and ear, the read range of a transponder can even increase in the vicinity of the tissue compared to free air (Adrion et al., 2015b). On the other hand, the ear tissue can absorb the radiation of the antenna and cause energy losses of the transponder antenna, so that reading gaps occur even close to the antenna (Nikitin and Rao, 2006). The ear tags are often obscured by other pigs, especially at a short trough, such as the one used in the experiment presented, because the pigs stand very close to each other during feeding. In combination, the negative and positive effects of the tissue lead to both false negatives and false positives. The orientation of the transponder to the antenna also influences the read range both positively and negatively. The use of antennas with an antenna field well-focused to the target detection area, in combination with the correct setting of the antenna output power, and the development of transponder ear tags with a low sensitivity to ear tissue and an omnidirectional directivity pattern could reduce this effect (Rao et al., 2005). Maselyne et al. (2014) also pointed out that, independent of the RFID frequency used, the position and characteristics of the pigs' ears and their individual behaviour can influence the sensitivity of an RFID monitoring system strongly, as shown in Fig. 4. These effects can change over days and over the fattening period. Consequently, tests with a higher number of animals and over several days from the beginning to the end of the fattening period should be carried out. The greater sample size would also reduce the influence of single events (e.g. a pig sleeping directly next to the trough) on the results. In this way, the accuracy of the performance parameters measured could be improved. However, if the prediction models in an early warning system for illness were based on the individual behavioural pattern of each animal, the individual differences in behaviour might not be detrimental (Maselyne et al., 2014).

As described in Section 3.3, high correlations between RFID data (registrations, TNUM, TDUR) and video data could be used to prove a correct estimation of TNUM and TDUR despite a difference between the actual and the target detection area. Furthermore, in some cases the evaluation of daily feeding time estimated in this way might be sufficient for health monitoring (Brown-Brandl et al., 2013). Diverging results regarding the correlations between RFID and video data were obtained for the free-form antenna and the patch antennas. The TDUR was predicted better by the number of RFID registrations (R^2 0.66 at 26 dBm) than by the TDUR of the RFID visits for the free-form antenna (R^2 0.6 and 0.56 at 26 dBm). It was the other way around for the patch antennas. The highest correlations for the patch antennas were measured at 25 dBm (R^2 0.8 and 0.78 for TDUR of RFID visits). This reflects the comparatively good results of this variant in terms of deviation between video and RFID data, and precision. Maselyne et al. (2016) calculated a coefficient of determination of 0.66 for the regression between the TDUR observed and the number of RFID registrations using one ear tag per pig. This value was 0.75 for the regression between the TDUR observed and TDUR of the RFID visits (min. duration of 1 s and bout criterion of 20 s) in their study. The TNUM observed was predicted by the TNUM of the RFID visits with an R^2 of 0.70. These values are within the same range as those measured using the UHF system with the free-form antenna at 26 dBm and the patch antennas at 25 dBm (see Table 6).

A valid comparison of these two different antenna types is not possible with the data of this study because of the low number of focal animals and changing number of animals in the pen. However, promising results were achieved with both variants. In summary, the trough visits of the focal pigs observed were detected best with the patch antennas at 25 dBm output power and a bout criterion of 30 s regarding the average precision and the correlation between the video data and the RFID visits. Other variants resulted in higher sensitivity, but simultaneously in lower precision, greater mean absolute deviation, and lower correlation between video and RFID data. Nevertheless, a high correlation between video and RFID data was also found with the free-form antenna at 26 dBm. This antenna could be preferable for some applications because of its high flexibility, slim design and the possibility of covering the whole length of the trough with only one antenna.

4. Conclusions and outlook

The suitability of a UHF-RFID system for monitoring trough visits of growing-finishing pigs was tested for the first time in literature. With the exception of a lower precision, the best validation results of the UHF-RFID system were comparable to those of Maselyne et al. (2016) applying HF-RFID at a round trough and, in terms of accuracy, also with the LF-RFID system developed by Brown-Brandl and Eigenberg (2011). It can be concluded that UHF-RFID can be suitable for the monitoring of trough visits of growing-finishing pigs. However, the results showed that UHF-RFID transponder ear tags are very sensitive to influence from surrounding tissue, leading to both false positive and false negative registrations. Further development of the transponders should reduce these effects by, for example, targeted detuning of the transponder antenna or application of transponder chips with an auto-tuning function to compensate for the change in resonance frequency the tissue causes.

On the other hand, UHF-RFID offers a great variety of forms and types of antennas that allow for the observation of very different detection areas and even complete pens (Adrion et al., 2016). Furthermore, the variation of the antenna output power makes it possible to adjust the reading area very flexibly, for example, to various types of transponders.

The results of this study should be seen as a first test of UHF-RFID for behaviour monitoring of pigs. Further tests should be conducted with a higher number of animals and test days and with UHF ear tags of a correct size for pigs. The application of the UHF-RFID system should also be tested over a whole fattening period, at different kinds of hotspots, such as drinkers or playing material, and with different species, such as cattle, to evaluate the potential and utilize the flexibility of this technology completely for animal behaviour monitoring in general.

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GENERAL DISCUSSION

This thesis presented methods to measure the performance of UHF-RFID transponder ear tags with and without the influence of ear tissue, and the test and validation of a UHF-RFID system for behaviour monitoring of growing-finishing pigs. In the following, additional aspects, which were not covered in detail in Chapter 1 to 3, and the general suitability of UHF-RFID for application in livestock management will be discussed comprehensively. Some additional results will be presented and suggestions for further research to improve the experimental methods, technical components and data analysis will be given.

1 Experimental methods

1.1 Static test bench

The static test bench, which was presented in Chapter 1 and used for measurements of the influence of ear tissue on the performance of UHF transponder ear tags in Chapter 2, is different to standardised methods of transponder performance measurements. The read range of UHF transponders is generally measured with anechoic chambers or with transverse electromagnetic cells (Rao et al., 2005). These ensure measurements in an environment almost free of multipath signals that can affect the measurements. The read range is measured in these chambers by step-wise reduction of the antenna output power. The maximum read range is represented by the lowest output power at which the transponder still responds to the reader signal. A theoretical read range can be calculated for any level of antenna output power by considering the distance between the reader antenna and transponder in the chamber, and for all directions of view by rotating the transponder. In addition, a read range profile of the transponder in a certain frequency range can be measured by varying the transmission frequency (Rao et al., 2005; Nikitin and Rao, 2006; Derbek et al., 2007). Thus, a comprehensive analysis of transponder performance is possible using this method.

On the other hand, direct performance measurements have clear advantages, such as those with the test bench presented. These measurements can take place in an environment similar to the targeted environment of application and the shape of the reading area can be measured directly. This makes measurements with different numbers and arrangements of antennas possible to evaluate, for example, the shape and overlap of reading areas in an antenna grid for cell of origin localisation (Adrion et al., 2016). Hence, not only transponders, but also reader antennas can be compared on such a test bench in terms of performance and geometry of the reading area. The influence of reflections from the surroundings can also be visualised. As long as these reflections do not change significantly during a test, comparisons between transponders are not impaired. In addition, fuzzy outer regions of the reading area, where readings only take place in the case of positive interference of the multipath signals, can be identified and give an estimation of the expectable variance of read range in the practical application due to this effect.

However, for measurements in which the transponders are not tested in free air, a reduction of reflections in the surrounding area by partly encasing the test bench with absorbing materials, which are typically polymers filled with ferrite or carbonaceous particles (Qin and Brosseau, 2012), could improve the precision of the measurements. The results presented in Chapter 2 indicate that pig and cattle ears have a strong influence on the transponder performance, partly originating in the absorption of multipath signals. A reduction of these signals could make differentiation between the influence of multipath absorption and the direct influence of the test materials by absorption of radiation from the reader, gain penalty and tag resonance shifting possible. Due to the high costs of HF-absorbing materials, installation should be carried out initially at the back side of the test bench, opposite to the reader antenna, and subsequently at other locations where a major part of the reflections can be expected. The absorber material should be mounted in a way that it can be shifted and removed easily to be adapted to current experimental objectives.

In summary, the static test bench constituted the basis of transponder evaluation and comparison during the research project and produced valuable information for the comparison, choice and further development of UHF transponder ear tags. Even though its measurement results are not generalizable, the test bench is a reasonable compromise between financial and methodical expense and the accuracy and benefits of the results.

1.2 Measurements with animals' ears and tissue models

It was concluded from the tests with ears and tissue models presented in Chapter 2, that the positioning of the ear tags on the ears probably did not exactly reproduce the conditions with live animals' ears, especially in the tests on the back side of pig ears. A possible approach to represent the real application better could be to not only use the female part of the ear tag, into which the transponder is integrated, but to apply the complete ear tag (male and female part) as it would be done with animals. The ears, therefore, would have to be prepared with a hole at the position desired. Additionally, the ear tags would have to be manipulated in such a way that the connection between the male and female part could be easily disassembled. A specially prepared male part could be used with all female ear tags to be tested to ensure comparable mounting and a fast changing of ear tags between test-runs. Furthermore, the ears should be rather hung up or at least fixed on the top of the holder to prevent their deformation due to their weight. In this way, the ear tags could be mounted on the ears, as they are on the animal in practice.

The second methodical conclusion drawn from the tests with ears and tissue models was that the tissue models did not represent the properties of the cattle and pig ears well. A solution for this would be not only to search for a material that fits the dielectric properties of the ears perfectly, but to shape the tissue models in a similar way to real pig and cattle ears. Kuster and Burkhardt (2000) pointed out that, in most cases, electromagnetic phantoms with simplified ears were used for measurements of the specific absorption rate of human heads, and that may have underestimated exposure in some cases. Based on numerical simulations, the authors proposed the composition of an experimental model of the human ear to reproduce the shape and dielectric properties of the pinna well, and include the influences of air cavities in the inner ear. The process of designing a numerical tissue phantom as a basis for the creation of an experimental model is complicated and relies on detailed magnetic resonance imaging (Kuster and Burkhardt, 2000; Christ et al., 2005). A sufficient variety of differently shaped pig and cattle ears would have to be evaluated to extract the average anatomical properties for the creation of the model. This simplification would lead to a much higher repeatability of measurements compared to those with real ears (Christ et al., 2005). It is questionable though whether this major effort would be worth the investment regarding a method for electronic ear tag optimisation. Since no health-relevant absorption measurements have to be conducted, and only the general function of the electronic ear tags near ear tissue is of interest here, the costs of numerical simulations and the generic phantom material would probably exceed the benefits. The optimisation of the measuring method with fresh pig and cattle ears, presented in Chapter 2, regarding the influence of multipath signals and the mounting of the ear tags seems more promising. Of course, a sufficient number of different ears have to be used in each test to represent their natural variation adequately and to allow for sound statistical test designs. Tests of the ear tags in animal trials could also be reduced using this method, which is highly favourable from the viewpoint of animal protection and to reduce research costs.

In conclusion, the first measurements of the influence of pig and cattle ears on the performance of UHF transponder ear tags delivered an estimation of the extent of this influence and provided new insights for understanding the performance of the ear tags in practice. However, further improvements, as discussed above, must be made and the results validated in practice to fully establish this method of measurement as a part of UHF transponder ear tag development.

1.3 Validation of the RFID system for behaviour monitoring

In Chapter 3, a UHF-RFID system was tested and validated for the detection of trough visits of growing-finishing pigs. The validation was carried out by a comparison of video and RFID data, which is a standard method for such systems that has been applied for cattle and pigs (DeVries et al., 2003; Chapinal et al., 2007; Reiners et al., 2009; Brown-Brandl and Eigenberg, 2011; Maselyne et al., 2014). The video analysis conducted in Chapter 3 only distinguished whether a pig was in the target area, but did not determine whether it was feeding. Since the RFID system was not able to distinguish between feeding and non-feeding events, too, this was not *per se* detrimental for the current analysis. However, a more detailed behaviour scoring in and around the target area, in this case – the trough, would be necessary to analyse whether a certain behaviour contributes especially to false negative or false positive registrations. Maselyne et al. (2016b) could, thus, identify the most important behaviours that led to false identifications, which were exploratory and agonistic behaviour, and inactivity (including lying, standing, sitting, kneeling, urinating and defecating) in their study. Moreover, the reading area of the RFID system could be adjusted at certain locations, for example, at a nipple drinker, in a way that the probability of registering a pig only when it is drinking could be relatively high. Thus, it would be interesting to calculate performance measures not only for the presence of the animals in the target area, but also for real drinking events. The video analysis should be adapted accordingly in further studies.

The validation in this study was conducted shortly before the end of the fattening period of the test animals. Since UHF-RFID ear tags are influenced by the surrounding ear tissue, it is possible that this influence changes the performance parameters over the fattening period due to the growth of the animals, especially their ears. The validation of the system should be conducted, at least at the beginning and the end of the fattening period, and desirably also in between, to measure this effect. In addition, the transponder ear tags should be tested in the laboratory, for example, on the static test bench, before and after the experiments to detect performance changes due to damage of the transponders. This information would be very important to further develop the ear tags in terms of sensitivity to ear tissue and durability. For the latter, the lifetime of the animals should be the minimum period (ISO TC23/SC19/WG3 Project Team on Additional Technologies, 2014). However, these effects would not be detrimental for behaviour monitoring if they had a consistent development over time. In this case, they could be extracted from the data together with all other effects that change constantly over time and, thus, would not affect the creation of, for example, health prediction models.

Two comparatively simple methods have been used for the estimation of a bout criterion to create visits from the RFID raw data, following Brown-Brandl and Eigenberg (2015) and Maselyne et al. (2016b). The trough visits must not be equated with meals, which are theoretically defined as “a group of sequential feeding visits during which the animal can perform other behaviours such as drinking, but is still busy with the concept of eating” (Maselyne et al., 2016b). Accordingly, meals represent a biological concept of feeding behaviour and summarise single events of feed intake. Meals are more difficult to define than feeding or trough visits. The determination of a meal criterion from feeding data is conducted mostly mathematically, considering meals to be either randomly (Poisson) distributed or based on the concept of satiety (Maselyne et al., 2015). The concept of satiety hereby seems to be more congruent with biological findings (Tolkamp et al., 1998). Tolkamp et al. (1998) and Tolkamp and Kyriazakis (1999) estimated a meal criterion by investigating the frequency distribution of log-transformed feeding interval lengths, an approach that fits the concept of satiety well. The distributions obtained had mostly two local maxima, one for within-meal intervals and one for between-meal intervals, and a minimum in between, which determined a suitable meal criterion (Fig. 1). It would be interesting to analyse the raw data from a RFID system in the same way. In contrast to the data of Tolkamp et al. (1998), which originated from a monitoring system that measured complete feeding visits, RFID raw data consist of single registrations which are completely disaggregated. Thus, the frequency distribution of the log-transformed registration interval lengths might show three local maxima: one for within-visit intervals, one for between-visit or within-meal intervals, and one for between meal intervals. In this way, a visit and a meal criterion could probably be obtained in one analysis.

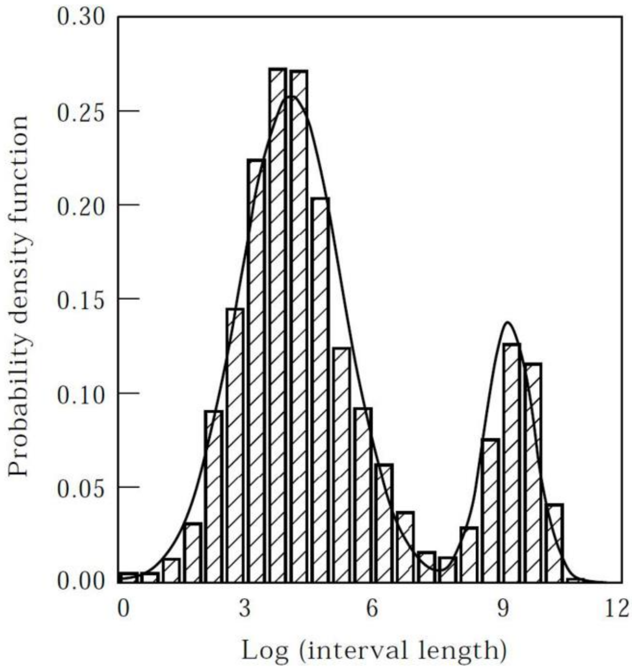

Fig. 1 Observed values (bars) and probability density function of the fitted log normal model of feeding intervals of dairy cattle (Tolkamp et al., 1998).

In conclusion, the validation of the UHF-RFID system presented here can be seen as a first step of the assessment of UHF-RFID for behaviour monitoring of livestock. The methods used could prove that UHF-RFID is generally suitable for this task, but the improvements of the validation process mentioned above must be applied for a more comprehensive evaluation. In addition, the validation should be extended to different species, especially cattle, and to different kinds of observation locations, such as drinkers and playing devices, and whole barn compartments, such as lying areas. Moreover, a deeper investigation of visit and meal criteria could lead to interesting results not only for the characterisation of animal behaviour, but also for the finding of informative variables for models monitoring health.

2 Possible range of applications and general suitability of UHF-RFID for the identification of livestock

The strengths and weaknesses of UHF-RFID technology for electronic animal identification have been demonstrated with measurements in the different parts of this thesis. In the following, these aspects will be discussed in summary, accompanied by additional results, to give a more detailed picture of the suitability of UHF-RFID for different applications in livestock farming at the current state of development and to give an outlook to future developments.

2.1 Mandatory animal identification

The simultaneous registration of groups of animals over variable reading distances using UHF-RFID offers a range of new applications for electronic animal identification. However, these additional possibilities are not decisive for the official accreditation of the technology. There are several basic requirements that an electronic identification technology has to fulfil before it can be approved for use in accordance with regulations for animal identification. The ISO project team on additional applications for electronic animal identification defined such requirements (ISO TC23/SC19/WG3 Project Team on Additional Technologies, 2014):

- Retention: The new technology should last at least for the lifetime of an animal.
- Readability: The visual and electronic readability has to be maintained in various climatic conditions (cold to hot, arid to humid, rain and snow, high exposure to ultraviolet radiation) and in various environments (e.g. barn, sales market, abattoir).
- Interoperability: Hardware and software of the new technology should be designed so that they can operate parallel to current standard technology without impairing its function.
- Compatibility with ISO 11784: The new technology has to be integrated with the current numbering scheme for official animal identification.

Additional requirements that are not mentioned in this document are, for example, mechanical and electronic protection of electronic ear tags against fraud, animal friendliness regarding the attachment to the ear and chemical safety. These requirements together with interoperability and compatibility are rather basic aspects that should be comparatively easily addressable for UHF developers due to the experiences made with LF-RFID. By contrast, extensive tests are demanded for proof of sufficient durability and readability. Regarding pigs for meat production (weaners and growing-finishing pigs), for example, at least 10,000 devices should be tested on a minimum of ten farms on at least two continents, covering northern and southern climates, for a period of at least three years (ISO TC23/SC19/WG3 Project Team on Additional Technologies, 2014).

Considering the results presented in this thesis and by Hammer et al. (2015; 2016a; 2016b), and the results of other projects (Moxey, 2011; Baadsgaard, 2012; Hogewerf et al., 2013; Pugh, 2013; Rosei Project Group, 2013), UHF-RFID for animal identification is still at an early stage of development and further progress has to be made to meet all the requirements for official use. The readability and retention of ear tags, especially, and the adaption of readers and antennas to the harsh environmental conditions in animal husbandry are not sufficient yet. Because of this and the high efforts of official testing, it is more likely that the first commercial applications of UHF technology will be in on-farm livestock management. If the technology proves its suitability there, the accreditation for official use will also be achievable.

2.2 Behaviour monitoring in comparison with LF-RFID

The simultaneous identification of animals is hardly possible with LF-RFID, at least when using just one antenna, thus, UHF-RFID should be more appropriate for the observation of locations that can be accessed by more than one animal at a time. However, a parallel comparison of the two technologies for this application has not yet been carried out. First of all, the performance of both technologies is of interest especially at small registration areas which can only be accessed by two to four animals at a time. During the experiment presented in Chapter 3 a parallel observation of a playing device for growing-finishing pigs with LF-RFID and UHF-RFID was carried out to investigate this. A short overview of these tests is shown here.

An LF antenna (purpose-built APA204, 41 x 21 cm, Agrident GmbH, Barsinghausen, Germany) was placed on the left side and a UHF antenna (MIRA-100-circular-ETSI, Kathrein RFID, Stephanskirchen, Germany) was placed on the top of the straw-filled metal container ("Porky Play", Zimmermann Stalltechnik GmbH, Oberessendorf, Germany) for the experiment (Fig. 2). The LF antenna was operated by a reader with a multiplexer (ASR550 and AAS100, Agrident GmbH, Barsinghausen, Germany) and the UHF antenna was connected to the same reader as the trough antennas in Chapter 3. The UHF antenna was operated with 23.4 dBm output power and circular polarisation, the rated carrier power of the LF antenna was approximately 43.2 dBµA/m at 10 m distance. Between one and two registrations of a transponder could be registered per second using the LF system. All 25 pigs in the test pen were tagged with a half-duplex LF ear tag (type HP, Allflex Europe SA, Vitré, France) in the left ear, so that the focus animals had a LF ear tag in the left and a UHF ear tag in the right ear. The playing device was 60 cm long, 50 cm wide and 100 cm high. A half circle with a radius of 45 cm around the centre of the UHF antenna was defined as the target area for registration. This included a small area in front and a very narrow strip of floor to the left and right of the playing device, where the pigs were often feeding on spilled straw. The rest of the test set-up and the test procedures were the same as in Chapter 3. A brief excerpt of the data of seven focal animals on test day 6 is shown in the following. One focal animal which was excluded from the analysis in Chapter 3, because its ear tag lost its function later in the experiment, was included in this analysis. The raw registrations were aggregated to visits with a minimum duration criterion of 1 s and a bout criterion of 70 s, which was determined with the graphical method of Brown-Brandl and Eigenberg (2015), for the calculations of the performance parameters. Additionally, the coefficients of determination (R^2) of linear regressions of the number of registrations (RFID raw data) and the total daily duration (TDUR) of the RFID visits against the TDUR of the video data were calculated.

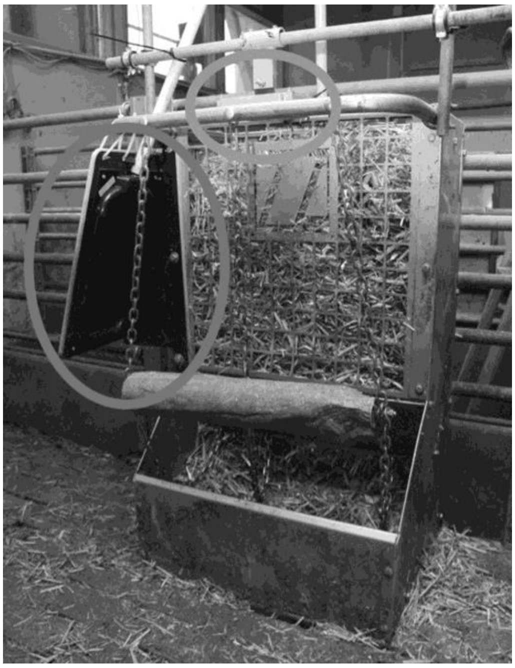

Fig. 2 Mounting positions of UHF-RFID antenna (right circle) and LF-RFID antenna (left circle) at the playing device (“Porky Play”, Zimmermann Stalltechnik GmbH, Oberessendorf, Germany) (Picture: Florian Eckert, 2015).

The LF- and UHF-RFID registrations of the seven focal pigs are shown in Figure 3 for a period of 4 h on day 6 of the experiment. It can be seen that the LF system recorded more registrations than the UHF system. A total of 6,239 registrations of the seven focal pigs were registered with the LF system, but only 2,243 with the UHF system between 11:00 and 22:00 on that day. Some of the registrations were also recorded with a major temporal distance to video events using the UHF system.

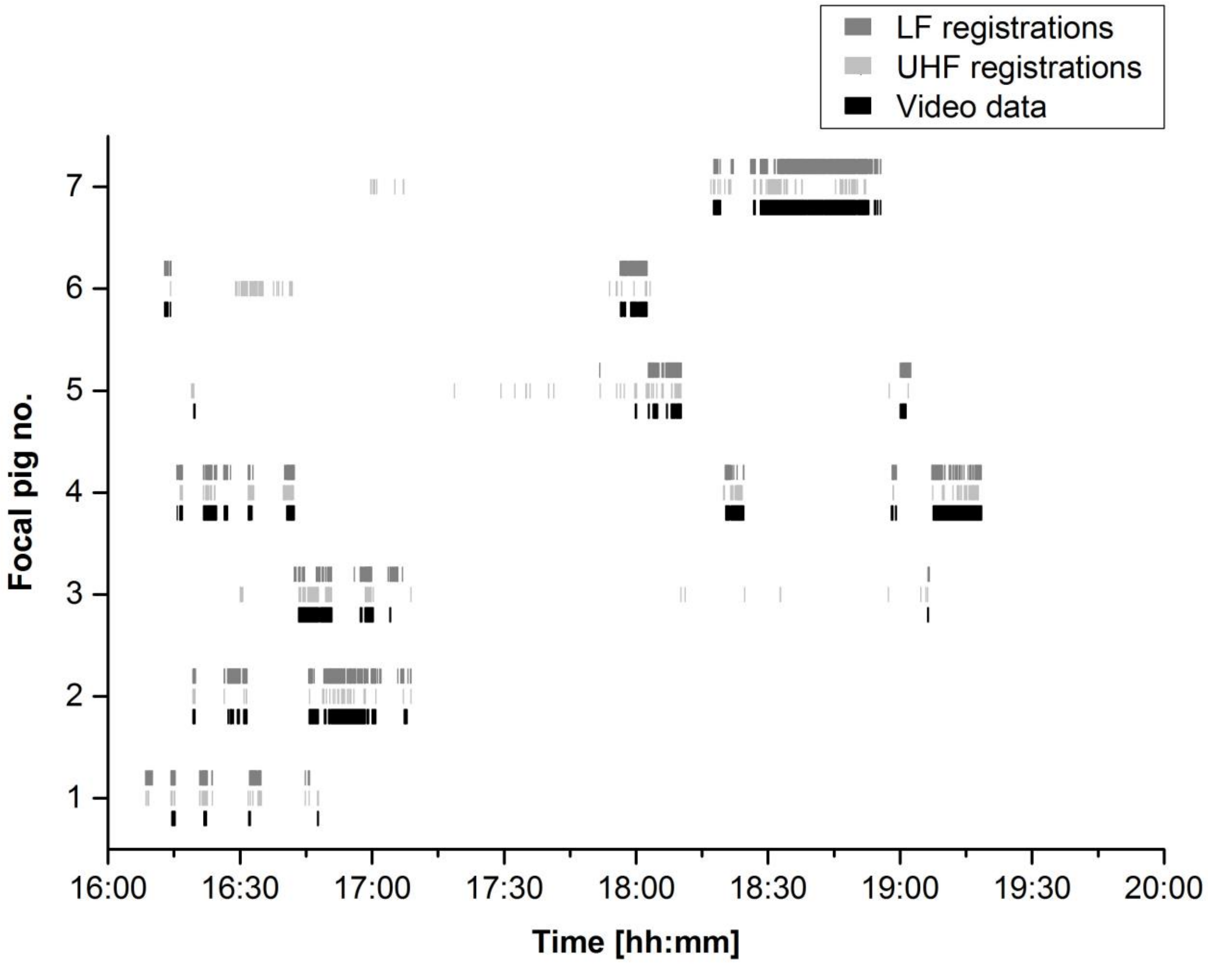

Fig. 3 The LF- and UHF-RFID registrations (raw data) at the playing device in combination with video data. Data of the seven focal pigs on day 6 between 16:00 and 20:00.

The coefficients of determination (R^2) of the linear regressions of the number of RFID registrations against the TDUR of the video data were also higher for the LF system. However, the coefficients of determination of the linear regressions of the TDUR of the RFID visits against the TDUR of the video data were much closer together (Table 1). The analysis of the performance parameters for the visits created from the raw data of both RFID systems showed that the LF system performed better in terms of sensitivity, while specificity, accuracy and precision were within the same range for both systems. Precision was below 60 % for both systems, indicating that the number of false positives was high, similar to the measurements at the trough in Chapter 3.

Table 1 Mean ± SD of sensitivity, specificity, accuracy and precision of the RFID visits to the playing device calculated with a minimum duration criterion of 1 s and a bout criterion of 70 s for the LF and UHF antenna, and coefficients of determination (R^2) of the linear regressions of the number of registrations (RFID raw data) and the total daily duration (TDUR) of the RFID visits against the TDUR of the video data; data of seven focal pigs on test day 6. R^2 of non-significant regressions were removed from the table (n.s.).

RFID system	Sensitivity [%]	Specificity [%]	Accuracy [%]	Precision [%]	R^2 TDUR raw	R^2 TDUR visits
UHF	62.5 ± 15.5	98.9 ± 0.7	97.7 ± 1.4	58.9 ± 25.1	n.s.	0.83
LF	85.5 ± 10.7	98.5 ± 0.5	98.2 ± 0.6	56.3 ± 19.5	0.91	0.95

The results showed clearly that the pigs' visits to the playing device were monitored by the LF-RFID system very well. Only the specificity and precision of the LF visits indicated a high number of false positives. Since only one antenna variant was tested with each system, it cannot be stated that the UHF system will generally perform worse than the LF system at this location. A different type or position of the UHF antenna or a different UHF ear tag may have resulted in a better performance. However, it is obvious that LF-RFID profits a lot from the low energy absorption rate of the ear tissue at its operation frequency. This allows for registrations of the transponders even when they are covered by tissue. On several occasions, two pigs were visiting the device simultaneously (Fig. 3). That did not impair the performance of the LF system very strongly. Focal pig no. 2 and 3, for example, were partly registered quasi-simultaneously during their visit around 16:45.

This example underlines that further research is needed to increase the reliability of registration for the UHF system, especially by the development of ear tags that are less sensitive to ear tissue. Further tests should also be conducted at locations which are visited by a higher number of pigs simultaneously to investigate how many pigs can be identified in parallel by the LF system despite collisions in the communication process between the transponders and the reader. Thus, how many animals have to be identified in parallel to really profit from the simultaneous identification of transponders with the UHF system could be determined. It is conceivable that both technologies could be used in parallel on farms, each where it performs best.

2.3 Monitoring and prediction of animal health and welfare

Animal behaviour can be an indicator of illness and welfare problems (Weary et al., 2009). The behavioural data recorded using RFID systems could, thus, be used in automatic monitoring systems that support the farmers in their daily observations of the animals (Frost et al., 1997; Madsen and Kristensen, 2005). In this way, sick animals could be detected earlier, and treatment costs and losses due to a decrease in production could be lowered. Some first tests of this application can be found in literature, for example, for dairy cattle (González et al., 2008), sows (Hinrichs and Hoy, 2010) and growing-finishing pigs (Maselyne et al., 2013; Brown-Brandl et al., 2016). All these studies found a large inter- and intra-animal variance of behaviour, therefore, prediction models for abnormal behaviour due to illness were difficult to create. Animals that visit the detection area, but do not consume water or feed are an additional source of error for systems that do not record the amount of feed or water consumed.

The results of a first monitoring experiment with more developed UHF transponder ear tags of a size for pigs within the frame of this research project were presented by Kapun et al. (2016). In this experiment, 33 growing-finishing pigs kept in an outdoor climate barn were observed by the UHF-RFID system at the trough, the drinker, a toy in the outdoor area and at the door to the outdoor area. The analysis showed that the average daily duration at the trough of pigs with lameness or respiratory diseases (coughing) was lower than for healthy pigs. However, the daily duration at the trough could not be used for prediction due to the large variance of the data of both healthy and sick pigs. Consequently, additional variables have to be searched for to model illness successfully. The analysis indicated that the use of variables connected to circadian rhythms, such as the duration of the night-time break, could be promising. Covariates, such as air temperature and humidity, also have to be considered to explain a part of the variance observed.

In conclusion, health and welfare monitoring of animals seems to be possible with UHF-RFID, but major efforts should be made to create reliable prediction models. Online monitoring algorithms will only work on an animal-individual basis and should be dynamic to take changes of behaviour over the lifetime of an animal, social constraints and group dynamics, as well as influences of environmental conditions into account. Further research in this area should include the collection of a sufficient amount of behavioural data, the search for predictive variables and the test of a broad variety of modelling and prediction methods.

2.4 Further applications

Due to its flexibility, UHF-RFID technology offers some additional possibilities for new applications that have not yet been tested. The high read range enables particularly the monitoring of larger areas in the barn, so that the motion activity of the animals could be recorded. An experiment to investigate this approach was conducted within the frame of the research project at the Agricultural Sciences Experimental Station of the University of Hohenheim (Adrion et al., 2016). Ten patch antennas of the type that was used for the experiment presented in Chapter 3 were mounted horizontally above a pen for growing-finishing pigs. The pen was completely covered by this antenna grid, with each antenna covering an area of approximately 1.60 x 1.60 m. This method is called proximity positioning or cell of origin positioning (Liu et al., 2007). The position of a transponder is determined simply by assigning it to the position of the antenna, by which it is registered at a certain moment. Consequently, the maximum accuracy of such a system is determined by the distance between two antennas in the grid. Eight focal pigs were tagged with a UHF transponder ear tag of a size for pigs, developed within the project. Different levels of antenna output power and two mounting heights of the antennas (1.70 and 2.00 m) were tested in the experiment. The results showed that the definition of the sectors was insufficient and a substantial number of false positive registrations due to overlapping sectors were recorded. On the other hand, sensitivity decreased strongly at low levels of output power. This shows that it is difficult to read the UHF transponder ear tags from a greater distance above without generating readings in other sectors when the ear tags in these sectors incidentally have an optimal orientation to the reader. A solution for this could be an increased distance between the antennas to prevent overlap, accompanied by an increased risk of missing sector visits in the outer area of the reading field. Registrations recorded during this experiment were aggregated to sector visits of the pigs for further analysis. Walking distances were then calculated from these visits. Each change of a pig between antenna sectors added the Euclidian distance between the two sector centres to the walking distance calculated. The results were compared with reference data from video analysis. In the optimum variant, the distances calculated were 78 ± 22 % (mean ± SD) of the distances observed with a coefficient of determination $R^2 = 0.77$ of the linear regression of the distances calculated against the distances observed. This shows that this method, with some improvements, could be used to monitor the activity of animals in a simple way in the future. The company Cattledata GmbH (Augsburg, Germany) already offers a first commercial application of proximity positioning with UHF-RFID to detect heat and health disorders in dairy cattle (Reimink, 2016). The number of sector changes of a cow is used together with group-building of several animals to detect heat with this system.

Another possible future application of the UHF-RFID technology is the monitoring of animal- and environment-related variables by integrating sensors on passive UHF transponder chips. Examples of such sensor tags have been shown in literature, for example, for measurement of body or ambient temperature (Cho et al., 2005; Vaz et al., 2010; Yin et al., 2010), air humidity (Virtanen et al., 2011) or light intensity (Cho et al., 2005). Systems for temperature measurement with ear tags that are currently on the market are using power supply from a battery (McCorkell et al., 2014; Griffioen and Nebel, 2016). A great advantage of the passive UHF sensor tags is that they can operate without battery supply and, thus, could, in principal, stay on the animal for their whole lifetime without any maintenance. However, measurements of temperature and other body parameters from the outside of the animal can be influenced by environmental factors and, thus, lead to misinterpretations (McCorkell et al., 2014). It is expected that UHF transponder chips will be available with an extremely low energy consumption through further development, so that the integration of even more complex sensors, such as accelerometers, could be feasible with simultaneously high read ranges (Philipose et al., 2005). In future, UHF-RFID could, in this way, be a part of integrated management systems that supply farmers and other members of the production chain with decision support information and could control production systems automatically (Frost et al., 1997; Berckmans, 2008). Thus, the ideas of PLF and the Internet of Things could be implemented in livestock farming with this technology.

GENERAL CONCLUSIONS AND OUTLOOK

The development of UHF-RFID components for livestock management offers a wide range of applications, but also brings with it some technical challenges to make the technology completely suitable for this field of use. The most important task currently is to develop UHF transponders that are less sensitive to body tissue and to adapt reader technology to the harsh environment and the user requirements in animal farming. This development must be accompanied by research to provide objective information on the development process and the performance of UHF systems in certain applications. Thus, the constraints of UHF-RFID also have to be determined to evaluate which RFID technology fits each specific application best. Consequently, the objectives of this thesis were chosen to contribute to the scientific understanding of the application of UHF-RFID in animal husbandry.

The test bench presented facilitated measurements of the read range and RSSI of UHF transponder ear tags. The strong and highly variable influence of ear tissue next to the ear tags on these two parameters could be shown in tests with pig and cattle ears as well as tissue imitations. Promising results could be achieved with a transponder type whose antenna had been detuned to match the operating frequency of the reader under the influence of ear tissue. However, most measurements also showed a strong negative influence of the ears with this transponder type. Since many readings of the transponder ear tags in practice seem to take place when the ear tag is not touching the ear, the main conclusion from these experiments was that UHF transponder ear tags have to be developed which function well both in free air and next to tissue. This could be achieved by moderate detuning of the transponder antenna, with an omnidirectional antenna field, a broad bandwidth and highly sensitive transponder chips which allow for automatic tuning. The methodology of the experiments with ear tissue should be further improved to monitor and support this development. The placement of high-frequency absorbers around the test bench could lower the influence of interference on the results. Furthermore, the mounting of the ear tags has to be adjusted to represent the actual position of the ear tags on the animal better. The measurements with tissue imitations did not represent the results with pig ears well. The improvement of measurements with ears seems to be advantageous for this due to the high effort of developing a representative tissue model.

Promising results for the application of UHF-RFID for monitoring animal behaviour were obtained in a first test of the technology in growing-finishing pigs. The main trough visits of the animals could be detected with both patch antennas and a freeform antenna. However, the influence of ear tissue on the readability of the UHF transponder ear tags was visible in this experiment in terms of suboptimal sensitivity and simultaneously high rates of false positive detections. Further experiments should be carried out with a higher number of focus animals and at several dates during the fattening period to increase the reliability of the validation results and determine the influence of animal growth on the performance of the system. The aggregation of the RFID raw data to visits is important to ensure that the data represents the animal behaviour well. Further research should be conducted to determine suitable visit and meal criteria to support the determination of informative variables for the prediction of illness.

Possible applications of UHF-RFID in animal husbandry include mandatory animal identification, behaviour and health monitoring as well as activity measurements. The advantages and disadvantages of UHF-RFID compared to LF- or HF-RFID for certain applications must be evaluated for each case. However, UHF-RFID can facilitate behaviour monitoring of animals especially in larger barn areas which contain multiple animals, due to its functional characteristics. Future research in this area should include the collection of a sufficient amount of behavioural data, the search for predictive variables and the test of a broad variety of modelling and prediction methods for health and welfare impairments. Further applications of the technology, such as positioning and sensor integration, and the implementation of the principles of the Internet of Things in livestock supply chains could follow.

Although the negative influence of body tissue cannot be eliminated completely, the fast development of UHF-RFID technology is permanently supporting the development of UHF ear tags, readers and antennas for the livestock business and could make the advantages of this technology utilisable in the few next years (Umstatter et al., 2014; Das and Harrop, 2016). Harry Stockman published the first paper on “Communication by means of reflected power” in 1948 (Stockman, 1948). Since then, tremendous technological progress has been made in RFID and there is still a lot of innovation to expect from this technology in the future.

SUMMARY

The basic concept of precision livestock farming is the integrated monitoring and control of animal farming systems. A prerequisite for this is data acquisition on the level of the individual animal, which is only possible on a large scale by applying electronic animal identification. Radio-frequency identification (RFID) systems in the ultra-high frequency range (UHF, 860 – 960 MHz) offer the possibility of simultaneous detection of transponders and a variably adjustable read range of more than 3 m. Thus, UHF-RFID opens a broad variety of innovative applications regarding electronic animal identification. Until now, these systems were, however, only insufficiently adapted to the operating conditions in livestock farming.

In collaboration with industry partners, passive UHF-RFID transponders for integration into ear tags for cattle and pigs and readers have been developed and tested. The objective of this thesis was the adaption and assessment of this UHF-RFID system for livestock farming. In particular, 1) the construction and test of a static test bench for UHF-RFID ear tags, 2) the development of a method of measuring the influence of ear tissue on the performance of UHF-RFID ear tags, and 3) the application and validation of the UHF-RFID system for monitoring of trough visits of growing-finishing pigs should be carried out.

A static test bench, consisting of two linear drives, was constructed for measurement of the registration area and the signal strength of different UHF transponder ear tags. The drives facilitated positioning of the ear tags in defined orientations on a coordinate grid within the antenna field of a reader. The methodical pretests revealed a very good repeatability of measurements and a minor influence of test parameters on the results. Thus, the test bench was considered suitable for the test and selection of functional models of the UHF transponder ear tags for use in pigs and cattle. The installation of radiation-absorbing materials at certain locations in the surroundings of the test bench could further improve the measurement accuracy.

The plastic of the ear tag and the ear tissue influence the readability of a UHF transponder ear tag strongly due to the absorption of radiation, shifting of the transponder resonance frequency and a change in its directional characteristic. Consequently, the transponder ear tags developed in the frame of the research project were tested on the test bench with fresh pig and cattle ears from the abattoir. The results showed a notable increase of the measurement variance and a decrease in read range and signal strength. However, it could also be shown that a targeted shifting of the resonance frequency of the transponders can reduce this effect. This means that there is potential for development of UHF transponder ear tags with a high reliability of registration. Further optimisation of the testing procedures and validation of the results in practice are necessary to fully establish this measurement method as a part of UHF transponder ear tag development.

The feeding behaviour of animals is an important indicator for the occurrence of illness and can, thus, be utilised for the automatic detection of illness. The monitoring of growing-finishing pigs tagged with UHF transponder ear tags at a trough for group feeding was tested in an experiment with two antenna variants and validated with video observation data. Furthermore, two methods for determination of an optimum bout criterion for the creation of visiting events from the raw data were compared. Sensitivity for the detection of the animals at the trough was between 56 and 80 %, but the percentage of the true positive registrations was only 55 to 70 %. The reduction of the size of the reading area would have been necessary for a more precise detection of the feeding behaviour. However, the general suitability of the UHF-RFID system for behaviour monitoring in livestock could be demonstrated. The validation in further research should be extended to different species, especially cattle, and to different kinds of observation locations to fully assess UHF-RFID technology for this application.

The experiments supported the selection and further development of UHF transponder ear tags and reader antennas for application in livestock farming. A suitable test method for UHF-RFID technology in the fields of research covered was established and applied for the first time. It repeatedly became clear during the experiments that the greatest challenge for the application of UHF transponders in ear tags is the reduction of the sensitivity against ear tissue. In addition to the monitoring of animal health with UHF-RFID, further research could be carried out regarding the positioning of animals for measurement of motion activity, the combination of transponders with sensors, for example, to measure body temperature, and the utilisation of the technology for implementation of the Internet of Things in food supply chains.

ZUSAMMENFASSUNG

Das grundlegende Konzept des Precision Livestock Farming ist die ganzheitliche Überwachung und Steuerung von Haltungssystemen für Nutztiere. Voraussetzung hierfür ist eine einzeltierbezogene Erfassung von Tierdaten, die in großem Maßstab nur durch eine elektronische Tierkennzeichnung ermöglicht wird. Radiofrequenzidentifikationssysteme (RFID) im Ultrahochfrequenzbereich (UHF, 860-960 MHz) bieten die Möglichkeit der Simultanerfassung von Transpondern sowie eine flexibel einstellbare Lesereichweite von mehr als drei Metern. Sie eröffnen so eine breite Vielfalt innovativer Anwendungen der elektronischen Tierkennzeichnung. Bisher wurden jedoch UHF-RFID-Systeme nur unzureichend an die Einsatzbedingungen in der Tierhaltung angepasst.

In Zusammenarbeit mit Industriepartnern wurden passive UHF-RFID-Transponder zur Integration in Ohrmarken für Rinder und Schweine sowie Lesegeräte entwickelt und getestet. Ziel dieser Arbeit war die Anpassung und Bewertung dieses UHF-RFID-Systems für die Nutztierhaltung. Teilziele waren 1.) die Konstruktion und der Test eines statischen Prüfstandes für UHF-RFID-Ohrmarken, 2.) die Entwicklung einer Methode zur Messung des Einflusses von Ohrgewebe auf die Leistungsfähigkeit von UHF-RFID-Ohrmarken und 3.) die Anwendung und Validierung des UHF-RFID-Systems zur Aufzeichnung der Trogbesuche von Mastschweinen.

Zur Vermessung des Erfassungsbereiches und der Signalstärke verschiedener UHF-Transponderohrmarken wurde ein statischer Prüfstand, bestehend aus zwei Linearantrieben, konstruiert. Die Antriebe ermöglichten die Positionierung der Ohrmarken in definierter Ausrichtung auf einem Koordinatenraster im Antennenfeld eines Lesegerätes. Die methodischen Vorversuche ergaben eine sehr gute Wiederholbarkeit der Messungen sowie einen geringen Einfluss der Versuchsparameter auf die Ergebnisse. Folglich wurde der Prüfstand als geeignet beurteilt für die Vermessung und die Auswahl von Funktionsmustern der UHF-Transponderohrmarken zur Nutzung bei Schweinen und Rindern. Die Installation von Strahlungsabsorbern an bestimmten Positionen in der Umgebung des Prüfstandes könnte die Genauigkeit der Messungen weiter verbessern.

Der Kunststoff der Ohrmarke und das Gewebe des Ohres üben durch Absorption von Strahlung, Verschiebung der Resonanzfrequenz des Transponders sowie Änderung von dessen Richtcharakteristik einen starken Einfluss auf die Lesbarkeit einer UHF-Transponderohrmarke aus. Aus diesem Grund wurden die im Forschungsprojekt entwickelten Transponderohrmarken

am statischen Prüfstand an schlachtfrischen Schweine- und Rinderohren getestet. Es zeigte sich hierbei eine deutliche Erhöhung der Varianz der Messungen sowie im Mittel eine Verringerung von Lesereichweite und Signalstärke. Ebenso konnte jedoch gezeigt werden, dass eine gezielte Verschiebung der Resonanzfrequenz der Transponder diesen Effekt verringern kann. Somit besteht Entwicklungspotential für UHF-Transponderohrmarken mit hoher Erfassungssicherheit. Um diese Messmethode gänzlich als Teil der Entwicklung von UHF-Transponderohrmarken zu etablieren, ist die Optimierung der Versuchsdurchführung sowie die Validierung der Ergebnisse in der Praxis notwendig.

Das Fressverhalten von Tieren ist ein wichtiger Indikator für das Auftreten von Krankheiten und kann somit zur automatischen Krankheitsfrüherkennung genutzt werden. In einem Versuch wurde die Erfassung von Mastschweinen, ausgestattet mit UHF-Transponderohrmarken, an einem Futtertrog für die Gruppenfütterung mit zwei verschiedenen Antennenvarianten getestet und mit Videobeobachtungen validiert. Es wurden außerdem zwei Methoden zur Bestimmung eines optimalen Aggregationskriteriums für die Bildung von Aufenthaltsereignissen aus den Rohdaten verglichen. Die Sensitivität des Systems für die Erfassung der Tiere am Trog lag zwischen 56 und 80 %, jedoch lag der Anteil der richtig positiven Erfassungen nur bei 55 bis 70 %. Eine Verkleinerung des Lesebereiches wäre somit für eine genauere Erfassung des Fressverhaltens notwendig gewesen. Die generelle Eignung des UHF-RFID-Systems für die Überwachung des Verhaltens von Nutztieren konnte jedoch gezeigt werden. In weiteren Versuchen sollte die Validierung auf andere Tierarten, vor allem Rinder, und auf weitere Beobachtungsorte ausgeweitet werden, um die Eignung von UHF-RFID für diese Anwendung umfassend zu bewerten.

Die Versuche unterstützten die Auswahl und Weiterentwicklung von UHF-Transponderohrmarken und Lesegerätantennen für die Nutzung in der Tierhaltung. Es wurde erstmalig eine geeignete Testmethode für UHF-RFID-Technologie in den bearbeiteten Forschungsbereichen entwickelt und angewendet. Im Verlauf der Versuche wurde mehrmals deutlich, dass die größte Herausforderung für den Einsatz von UHF-Transpondern in Ohrmarken in der Minderung der Sensitivität gegenüber des Ohrgewebes besteht. Neben einer Überwachung der Tiergesundheit mittels UHF-RFID sind weitere mögliche Forschungsansätze die Lokalisierung von Tieren zur Messung der Bewegungsaktivität, die Kombination der Transponder mit Sensorik, beispielsweise zur Messung der Körpertemperatur, sowie die Nutzung der Technologie zur Implementierung des Internet der Dinge in Lieferketten für Lebensmittel.

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