Dual-Band Channel Gain Statistics for Dual-Antenna Tyre Pressure Monitoring RFID Tags

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***Abstract*—In this contribution we analyse the read probability enhancement using two simple dual-antenna techniques for passive RFID tags for Tyre Pressure Monitoring applications. Our analysis is based on real-world channel measurements carried out with a full vehicle body for different antenna and steering angle configurations. Two frequency ranges were analysed: European UHF band at about 866 MHz and 2.45 GHz ISM band. Two antenna combining methods were investigated: Antenna selection and power combining. With the latter a read probability enhancement from 49% to 75% is achievable.**

I. INTRODUCTION

Tyre pressure monitoring systems (TPMS) are in widespread use due to their proved safety enhancement and their positive impact on fuel consumption. While current systems often rely on battery based bulky sensor units mounted in the rim, current research tends to move the sensor directly to the tyre [1] and to eliminate the need for a battery. In the last years passive radio frequency identification (RFID) systems have proven to provide battery-less and contact-less data storage with considerable reading ranges. However, losses in the radio channel for TPMS using a single onboard unit (OU) antenna centered at the bottom of the car are quite high [2]–[4].

In this work we investigate the possibility to use passive RFID technology for data transfer between wheel units (WUs) containing sensors, and one centralised onbord unit. This is realised by connecting an RFID reader to the OU antenna and using WUs which are composed of a modified passive RFID tag attached to a pressure sensor. Our investigation is based on channel measurements gathered in [4]. With this channel measurement data, we compute read probabilities for single and dual-antenna tags. The benefits of multi-antenna techniques are well known also for RFID applications, both in theory [5] and in practical validation [6]. In contrast to existing work this paper is based on multiple channel realisations at various frequency points in two frequency bands, and provides a statistical channel description to give read probabilities for the dedicated scenario of RFID based TPMS communication.

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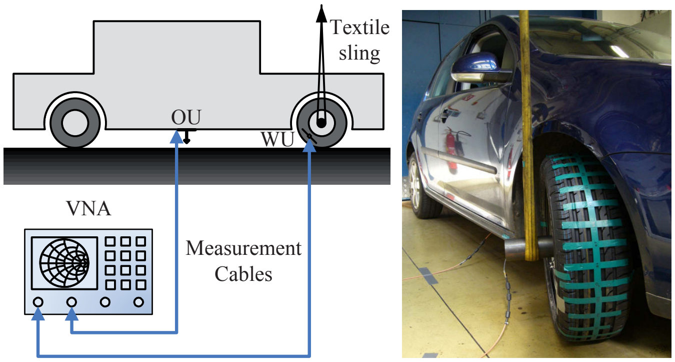


(a) (b)

Fig. 1. Measurement Setup.

II. CHANNEL MEASUREMENTS

The channel data used for the following analysis was acquired during a measurement campaign described in [4]. A schematical diagram of the used measurement setup is presented in Fig. 1(a). A Volkswagen Golf vehicle was equipped with a modified wheel at the front right position, which enabled to keep the non-inflated tyre at a normal height, mount WU measurement antennas at four different positions, and turn the wheel per hand to acquire measurement results for different rotational angles, as is shown in Fig. 1(b). The OU monopole antenna was mounted at the bottom of the vehicle, and was designed for dual-band operation for both desired frequency bands: The European UHF band ranging from 865 MHz to 868 MHz and the ISM band from 2.4 GHz to 2.5 GHz. Two different WU dipole antennas were used for the measurements, both manufactured from adhesive copper foil. The first one measures 10 mm×42 mm, the second one 10 mm×101 mm, both with a 1 mm gap between the dipole elements. The shorter dipole has been used for all mounting positions and for both frequency ranges. The smaller size enables measurements in all orientations, but in all cases this dipole is non-resonant. In the 868 MHz band comparison measurements were carried out with the long dipole, which is in resonance here.

Measurements in 10° steps of the rotational angle were per-

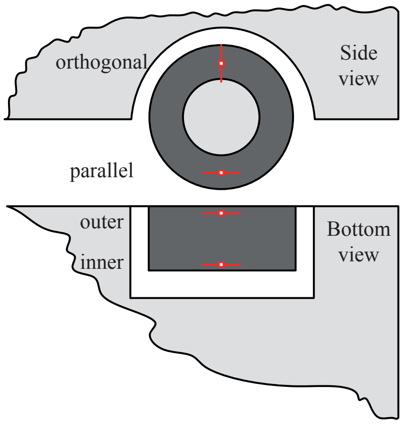
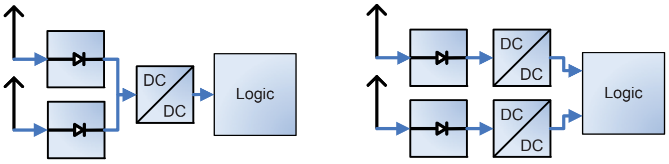


Fig. 2. Partial view of vehicle body describing WU orientations.



(a) (b)

Fig. 3. Signal combining techniques.

formed using a vector network analyser (VNA). De-embedding included removal of antenna-cable losses and matching losses for the nonresonant WU antennas at the topmost WU antenna position [4]. With the short WU antenna, four different mounting positions were measured, as indicated in Fig. 2. With respect to the vehicle centre, the dipole was mounted either on the inner or outer sidewall of the tyre. On that particular sidewall, the antenna could be oriented parallel or orthogonal to the tyre tread.

III. SIGNAL COMBINING TECHNIQUES

In the following section we compare the measured channels for a single WU antenna with virtual channels created when using dual-antenna tags. The use of two or more antennas enables diversity and potentially increases forward and backward link quality, as theoretically described in [5]. We will focus on the forward link, as the main concern for TPMS applications is powering the RFID tag, due to the high channel losses.

A. Antenna Selection

Antenna selection is a well known low complexity scheme to gain diversity in radio systems [7]. Implementation for RFID systems can be realized even simpler by using one rectifier circuit per antenna and paralleling the outputs, as indicated in Fig. 3(a). In the case of the first antenna receiving a stronger signal than the other, the output voltage of the corresponding rectifier will be larger than the one that would have been produced with the second rectifier. In this case the second antenna does not feed any power in the power conditioning circuits and therefore acts as being switched off. For the case of almost identical fieldstrengths at both antennas paralleling the rectifier outputs even gives slightly better results than classical antenna selection, because both rectifying circuits provide current for the tag's power supply.

B. Power Combining

In contrast to antenna selection, power combining enables exploiting the power simultaneously received at both antennas [8].

A simplified method is described in [9], where both antennas are connected to rectifiers, which are connected in series to implement a summation. Due to differing input powers, the rectifier's output impedances are unequal. Therefore, a compromise is required for the matching to the DC–DC converter when this simple approach is used. A more general case is shown in Fig. 3(b) which exploits the sum of the input powers of both antennas.

C. Practical Limitations

The efficiency of practical rectifiers and DC–DC converters depends strongly on input power due to the nature of semiconductor components [10], [11]. For the proposed antenna selection scheme using antenna switching, this dependency has negligible impact on our analysis since our investigation in Section IV-B is based on a tag sensitivity threshold.

The power combining approach operates two rectifiers and DC–DC converters at different input power levels and therefore has to cope with different conversion efficiencies of the mentioned circuits. Our further analysis of this approach is restricted to the case of ideal rectifier and converter circuits and therefore gives an upper bound for real implementations.

IV. STATISTICAL ANALYSIS

To gain insight to the read probability of an RFID sensor node mounted in the tyre, we use a randomization technique of the obtained measurement data. For a given WU antenna mounting position we pick a random rotational angle and frequency and evaluate the magnitude of the channel coefficient. For the 866 MHz band we evaluate all frequency points between 865 MHz and 868 MHz. The broadband measurement results carried out at the 2.45 GHz band were restricted to frequency points from 2.4 GHz to 2.5 GHz. This analysis is conducted either for the case of a steering angle being zero, or with the assumption that the three steering angles -25°, 0° and 25° at which measurements were performed are equally likely.

At the 866 MHz band the channel response primarily depends on rotational angle, and the measured 101 frequency points do not add much variation. Because the channel is very bandlimited with respect to the Fourier domain corresponding to the rotational angle [4], interpolation of the measurement points in the angular domain is possible without creating artifacts. This was done by calculating the Fourier series, padding zeros and converting back to angular domain, resulting in an upsample factor of 10. This method corresponds to a $\frac{\sin(x)}{x}$ interpolation of the channel magnitude measurement points to give 1° resolution. These samples were then randomised in the same manner as the original samples in the 2.45 GHz band.

Given a certain transmit power and tag sensitivity, communication is possible if the channel magnitude is high enough. This statement is based on the assumption that the channel stays constant throughout the whole communication process, including RFID chip wakeup time, query command and data exchange. When observing the channel measurement results over rotational angle [4], [12], this is valid for tyre rotations smaller than 10°. So for a tyre radius of 33 cm corresponding to a typical tyre dimension of 205/55R16 and a driving speed of 100 km/h our assumption is satisfied if the communication process is accomplished within 2 ms. For longer communication time the allowed speed has to be reduced accordingly, or a more complex analysis technique is necessary where the minimum channel magnitude over a certain time period has to be evaluated.

A. *Single Antenna Tag*

1) Results at the 866 MHz Band: Using the randomization technique described before, complementary cumulative distribution functions (CCDFs) for the four antenna mounting positions are drawn in Fig. 4, using the short WU antenna. While plotting cumulative distribution functions (CDFs) would give curves that directly relate to the outage probability, the ordinate of the used CCDFs gives the probability for the channel magnitude $|h|$ being above a certain value picked on the abscissa. To evaluate the read probability

$$P = \mathrm{P}\{|h| > h_{\mathrm{th}}\}$$

we first calculate the maximally allowed channel loss h_{th}. The combination of a state-of-the-art tag sensitivity of -17 dBm [13] and a transmit power of 33 dBm leads to a maximally allowed channel loss of 50 dB. Therefore, the WU tag with an inner parallel mounted antenna has a read probability P of 49%. For inner orthogonal, outer orthogonal and outer parallel mounting the read probabilities are 30%, 14% and 1%, respectively.

A comparison between the short non-resonant WU dipole and the longer resonant version for parallel mounting is depicted in Fig. 5. Due to the high slope of the CCDFs the efficiency improvement of approximately 5 dB of the long antenna corresponds to reading probabilities of 89% for the inner positioned antenna and 16% for the outer antenna.

2) Results at the 2.45 GHz Band: Fig. 6 compares the CCDFs for different mounting positions of the short WU dipole at the 2.45 GHz microwave band. Compared to the situation at 866 MHz the channel exhibits higher losses, therefore achieving approximately the same read probabilities demands an increase in transmit power or tag sensitivity by 12 dB.

To evaluate the effects of steering, the CCDFs for all four WU mounting positions including the equiprobable steering angles $-25°$, $0°$ and $25°$ are plotted in Fig. 7. Comparing Fig. 6 and Fig. 7, only minor changes at high channel gains are noticeable, so in most cases the effects of steering are negligible.

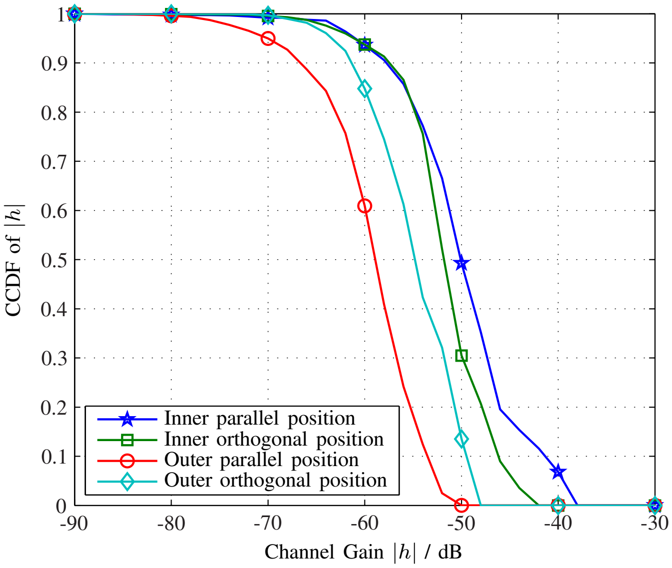


Fig. 4. CCDFs of channel magnitude for different WU orientations at 866 MHz.

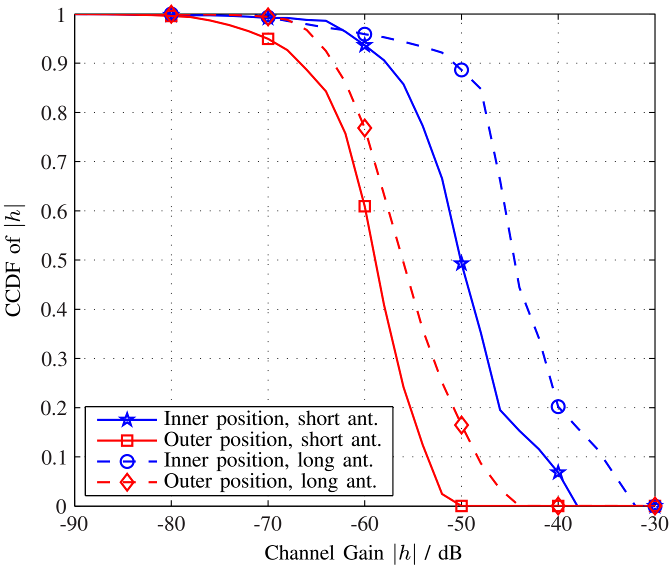


Fig. 5. CCDFs of channel magnitude for long and short parallel antennas at 866 MHz.

B. *Dual Antenna Tag*

We now combine two single antenna measurement data curves to form a virtual single input multiple output (SIMO) channel. In general, this is not valid, since antennas in close proximity influence each other. However, when using antennas with a symmetry plane for the electromagnetic field, and placing the first on the symmetry plane of the second (and vice versa), the antennas do not influence each other and can be measured separately.

Since we are joining measurements from dipole antennas which are at the same position but in different orientations being orthogonal to each other, this approach of calculating

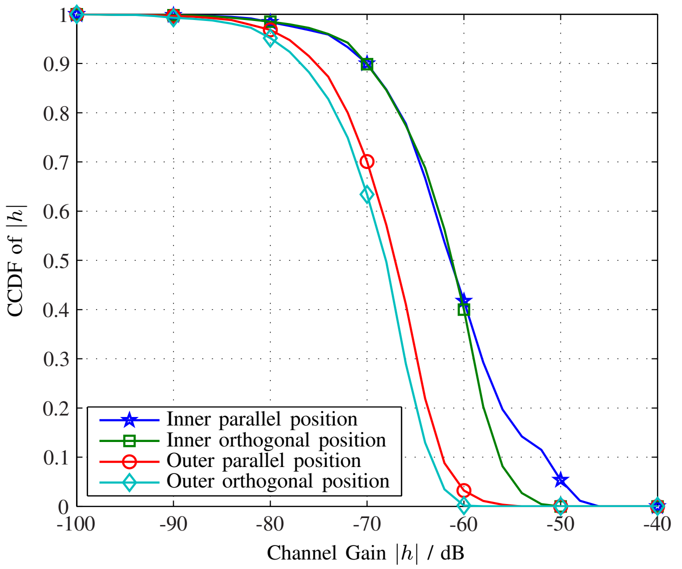


Fig. 6. CCDFs of channel magnitude for different WU orientations at 2.45 GHz.

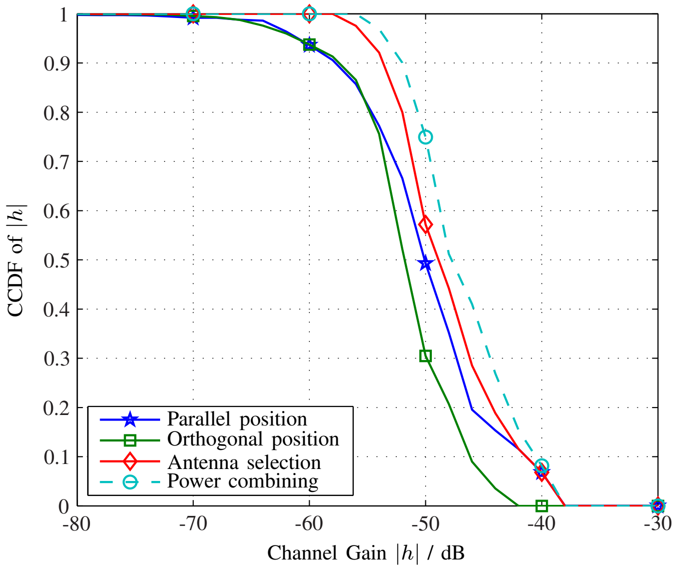


Fig. 8. CCDFs of channel magnitude at 866 MHz for inner mounted antennas and virtual SIMO channel.

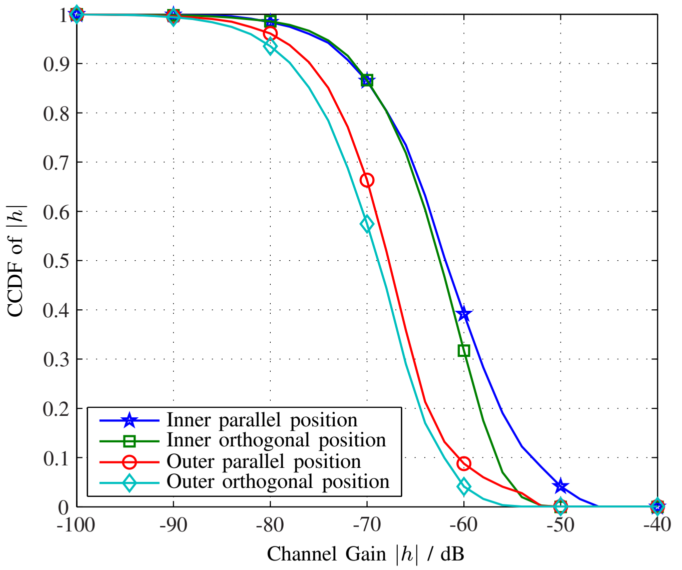


Fig. 7. CCDFs of channel magnitude for different WU orientations at 2.45 GHz, including steering angles left and right.

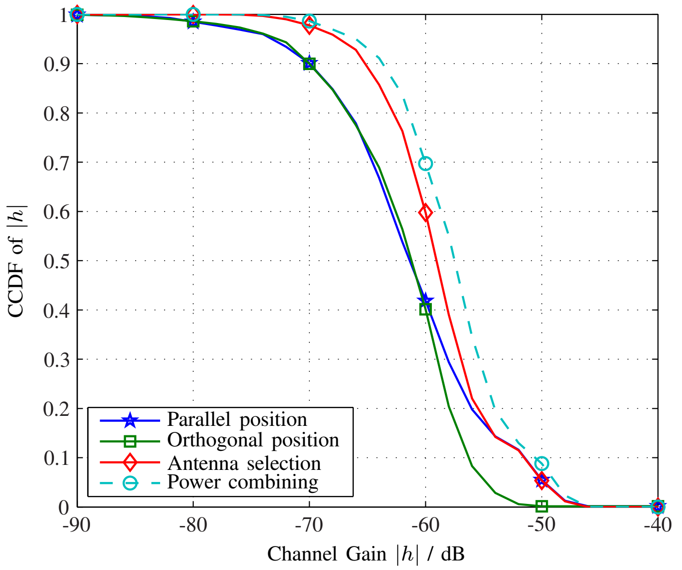


Fig. 9. CCDFs of channel magnitude at 2.45 GHz for inner mounted antennas and virtual SIMO channel.

the SIMO channel from the corresponding single input single output (SISO) channel is fully equivalent to really measuring the SIMO channels with both WU antennas in place at the same time. The SIMO channels were calculated according to the combining techniques discussed in Section III.

1) Results at the 866 MHz Band: Only the inner WU mounting position is analysed in Fig. 8 because it exhibits higher channel gains. The use of the simpler antenna selection technique leads to an increased read probability of 58%, the more advanced power combining technique even to 75% read probability. But even more important, the diversity gain realised by using two antennas dramatically reduces the requirements on tag sensitivity or transmit power, to reach 100% read probability: The necessary difference between reader transmit power and tag wake-up power is reduced from 75 dB to 56 dB for the power combining case.

2) Results at the 2.45 GHz Band: The improvement due to dual-antenna techniques is also eminent in the microwave band, see Fig. 9. Because both inner mounted antennas perform almost identical in lower gain regimes, the improvement due to the SIMO approach is evident here: The slope of the SIMO CCDFs is steeper than in the SISO case, enabling medium to high read probabilities with less stringent constraints on tag sensitivity or transmit power. The improvement of the more sophisticated power combining technique over the simpler antenna selection is merely 1.5 dB or less, so for

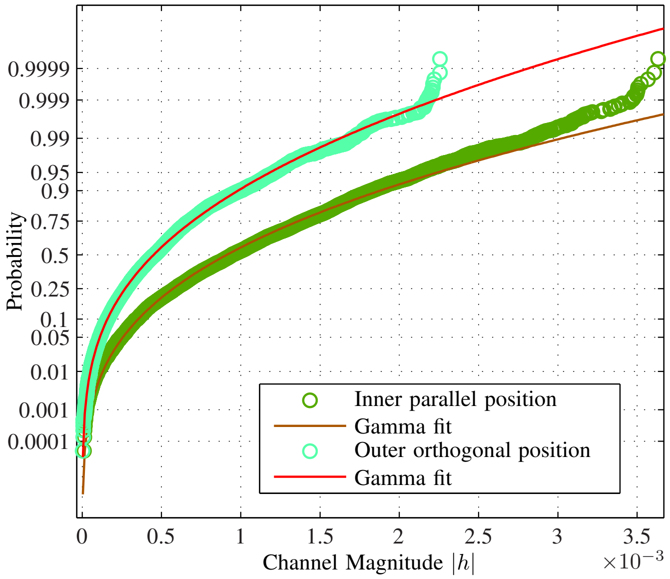


Fig. 10. Probability plot for gamma distribution fitting of channel magnitudes at 2.45 GHz band.

TABLE I
PARAMETERS OF GAMMA DISTRIBUTIONS FOR 2.45 GHZ BAND.

WU Antenna Position	Parameter a	Parameter b
Inner parallel	1.743	7.701×10^{-4}
Inner orthogonal	2.703	3.833×10^{-4}
Outer parallel	2.045	3.152×10^{-4}
Outer orthogonal	2.319	2.255×10^{-4}

practical chip design it might be more favourable to use the simpler approach.

V. STATISTICAL CHANNEL DESCRIPTION

Based on the randomisation technique explained in Section IV we used a minimum mean square error approach to fit the channel coefficients to a known distribution. For the 2.45 GHz band it was found that the gamma distribution with probability density function

$$f_X(x) = \frac{1}{b^a\,\Gamma(a)} x^{a-1} e^{-x/b} \quad \text{for } x > 0$$

and parameters a and b gives best results. We use the scenario with equiprobable steering angles which maximises the number of channel measurement points for the statistical fitting. Table I presents the parameters for the gamma distribution fitting for the four mounting positions. The quality of the fit is assessed by the probability plot, Fig. 10, which is shown for inner parallel and outer orthogonal mounted WU antennas. The ideal fitted curves of the gamma distribution closely match the actual measured values of the channel magnitude.

At the 866 MHz band the distribution of the recorded channel samples significantly departs from a gamma distribution, therefore we waive to give fitted values for this case.

VI. CONCLUSION

In this contribution, we analyse and discuss the channel magnitude statistics between an OU and RFID based WUs for tyre pressure monitoring applications. The real-world channel measurements were carried out in two frequency bands using a vehicle body and a modified tyre. We conclude that the communication between OU and WUs is limited in the forward link due to the high channel losses and the WU's passive RFID technology. We give the read probability for several WU antenna orientations based on state-of-the-art RFID tag sensitivity and the legal emission limits. CCDFs are estimated for instantaneous evaluation of the read probability for different tag sensitivities or transmit powers. Our results indicate that significantly enhanced read probabilities are achievable using dual-antenna WUs. We investigated and compared the simpler antenna selection technique with power combining. With the latter, the read probability for an inner mounted WU at 866 MHz band is increased from 30% to 75%, when compared with a single antenna WU. For both frequency bands the performance increase from antenna selection to power combining is at maximum 1.7 dB, i.e., the simpler technique implies a rather minor penalty. Finally, we document our gamma parameter estimates for the channel magnitude in the 2.45 GHz band.

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