Application of the UHF RFID System
for the Identification of Sportsmen in Mass Races

Milan Svanda¹, Milan Polivka², Premysl Hudec³

Abstract – A modification of a standard UHF RFID system for identification of sportsmen during mass races was proposed, realized and verified. Necessary improvements were motivated by initial tests that showed a very poor reliability of identification. The performed mathematical simulations and measurements indicated the system components that are decisive for correct identification, i.e. primarily, both the reader and the transponder (TAG) antennas, their radiation patterns, tilt and efficiency. The optimized RFID system was tested in a standard outdoor operation with several configurations of sportsmen moving with different speeds from approx. 4 km/h up to 15 km/h. The obtained final results show 100% identification reliability.

Index Terms – RFID, contact-less identification, patch antennas, transponders.

I. Introduction

The application of the Radio Frequency Identification (RFID) systems spreads into many fields, such as commercial, industrial, medical, scientific and other areas; basic information can be found e.g. in [1]. The optimal implementation of any RFID system depends on the geometry of the particular identification task and also on the operational frequency used. The low frequency RFID systems require a relatively strong magnetic coupling and, therefore, usually also a short distance among the reader and transponders. For the identification of a higher number of larger objects, substantially longer distances among the reader and transponders must be taken into account and the usage of higher frequencies can be recommended. In this case, the coupling is ensured by the propagation of the electromagnetic waves.

Each UHF RFID system usually consists of one reader and a number of transponders (TAGs) that are placed on objects that are to be identified. The reader consists of a transmitter and antenna that illuminates the TAGs with an electromagnetic wave of the given frequency and the power density required. Each TAG uses a part of the received energy for modulation of its antenna reflection coefficient with an individual code. The reflected and modulated signal reaches the reader antenna and is processed by a reader’s receiver.

A basic feasibility study [2] on using a standard commercial RFID system, see Table 1 and reference [3], operated in the 869 MHz band for the identification of moving objects (races running through the finish gate) was performed. The initial practical tests showed a very low reliability of identification. In order to identify the main system failures, several mathematical simulations and measurements were performed. The consequent system improvement and the optimization were focused on the components that showed the decisive influence on the reliability of identification.

The optimized RFID system is intended to be used for reliable identification of sportsmen in a finishing or checking gate, their precise time at the finishing line must still be obtained by another method.

II. RFID system power budget

The functionality of any RFID system is based on the reader-TAG power budgets. The TAG input power must be higher than its sensitivity (-6.9 dBm), which provides energy for the modulation of the reflected wave. In the same way, in order to ensure correct data processing, the input power of the receiver within the reader must be higher than its sensitivity (-64 dBm). The evaluations as well as the measurement of reader-TAG power budgets were performed by means of the modified two-ray model, see Fig. 1. The model works with one direct ray and one ray reflected from the ground. Moreover, the approximated 3D radiation patterns of both the reader and TAG antennas were taken into account. This modification improves relation of the model with respect to the reality. Furthermore, it enables the simulation of a general tilt of both reader and TAG antennas.

The propagation of an electromagnetic wave from the reader to the TAG can be described by means of the following link loss:

| Table 1. Standard UHF RFID system parameters (from [3]) |
|-----------------|-----------------|
| Parameter       | Values          |
| Operating frequency (Eur.) | 869.5 ÷ 869.7 MHz |
| Transmitted power | 24.7 dBm ÷ 36.0 dBm |
| Receiver sensitivity | -64 dBm (200pW) |
| Identification rate | 70 s⁻¹ |
| Reader antenna gain | 8.0 dBi |
| Chip sensitivity | -6.9 dBm (200µW) |
| TAG ant. gain in free space | 2.1 dBi |
| Chip impedance (meas.) | 76 - j340 Ω |
| TAG conversion loss | approx. 20 dB |

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\[ L = -20 \log \left( \frac{1}{10} \sqrt{G_t V(\alpha_d) \cdot \sqrt{G_r V(\beta_d)}} \right) \]

where \( r_1, r_2 \) are lengths of direct and reflected rays, \( G_t V(\alpha), G_r V(\beta) \) stand for angular dependences of the reader antenna gain in vertical and horizontal planes, \( G_t V(\gamma), G_r V(\delta) \) represent angular dependences of the TAG antenna gain in a vertical and horizontal planes, \( r(\psi) \) is a complex reflection coefficient of a wet ground (\( \epsilon_r = 10, \sigma = 10^{-2} \) S/m was considered).

The power received by the TAG antenna \( P_{r, TAG} \) in dBm can be expressed as follows:

\[ P_{r, TAG} = P_t - L - L_f \]

where \( P_t \) is a power transmitted by the reader in dBm, \( L \) stands for the link loss and \( L_f \) represents the attenuation of the feeder cable in dB. The peak power of the modulated signal reflected back from the TAG and received by the receiver within the reader \( P_{r, READER} \) in dBm can be expressed as follows:

\[ P_{r, READER} = P_{r, TAG} - L - L_f - L_{conv} \]

where \( L_{conv} \) is the conversion loss of the chip (approx. 20 dB).

### III. Reader and transponder antennas

Since the transmitted power \( P_t \) and TAG and reader sensitivities are given by the UHF RFID system used, see Table 1, both power budgets according to (2) and (3) are dominantly influenced by the parameters of the TAG and reader antennas used. TAG antennas are probably the most sensitive parts of the described RFID system. They operate in a close vicinity to human bodies, which can lead to an unacceptably low antenna efficiency. Consequently, the new types of TAG antenna were designed, realized and tested.

#### A) Reader antenna

In order to enhance the effective radiated power of the reader antenna and to focus the energy to the expected identification area, the reader antenna of microstrip patch collinear arrangement was designed [4]. It shows a wide radiation pattern in the horizontal plane and narrower pattern in the vertical plane with corresponding higher gain (11.7 dBi compared to original 8.0 dBi of the original antenna). Fig. 2 shows its radiation patterns. The gain enhancement 3.7 dBi in both power budgets according to (2) and (3) was achieved.

#### B) Transponder antennas

The best part of the contemporarily available UHF RFID systems employs the TAGs equipped with planar shortened-dipole type antennas. As for the main advantages of this antenna, it is possible to mention relatively small dimensions (typ. 80 × 50 mm), a low profile (typ. 0.5 mm), a low weight and favourable manufacturing costs. The planar dipole antenna dimensions and approx. 2 dBi gain (measured in a free space) could be acceptable even for the described application. Unfortunately, this type of antenna is very sensitive to any object situated in its near proximity. If such a dipole is placed on a human body, a substantial detuning of its impedance matching occurs. Measurement of the frequency detuning of a mean-der dipole [2] can be seen in Fig. 3. The de-tuning together with an absorption of electromagnetic waves in this lossy dielectric result in a very low antenna efficiency and consequently in an unsatisfactory antenna gain, see Table 2.
Planar meander dipole [2] return loss as parameter of distance \( b \) from human body phantom

Table 2. Measured gain of TAG antennas

<table>
<thead>
<tr>
<th>Antenna type</th>
<th>G [dBi]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meander dipole sample, free space</td>
<td>2.2</td>
</tr>
<tr>
<td>Meander dipole sample, ( b = 20 , \text{mm} )</td>
<td>-5.72</td>
</tr>
<tr>
<td>New patch, free space</td>
<td>6.3</td>
</tr>
<tr>
<td>New patch, ( b = 20 , \text{mm} )</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The antennas with a metallic ground plane likely represent the best solution of the above described problems. The ground plane increases the front-to-back ratio and reduces the influence of the human body on the antenna parameters. The planar patch antenna is probably the simplest ground plane antenna. However, at relatively low operating frequencies, several potential difficulties must be taken into account. Firstly, the basic patch resonant frequency corresponds to \( \lambda/2 \) and, therefore, at UHF frequencies the patch antennas cannot be extremely small. Secondly, at these frequencies the problems with low antenna efficiency can be expected because of low substrate thickness \( h \), see Fig. 4.

For the identification of the racers, the patch lengths around 170 mm (approx. of used frequency) does not necessarily represent the major problem, since these antennas can be, for instance, integrated into their number labels. The efficiency problems can be solved if the acceptable height and permittivity of an antenna dielectric are used. A very light and flexible foam with \( \varepsilon_r \rightarrow 1 \) and \( h/\lambda_0 \sim 0.014 \) turned out to be a very convenient solution. The TAG antenna is terminated with a chip. Since the chip input impedance is \( Z_{\text{chip}} = 76 \cdot j34 \, \Omega \), the antenna input impedance must be conjugate matched.

The new patch antenna [6], see Fig. 5, was fabricated on a foam dielectric (G3 9568 foam \( h = 4.8 \, \text{mm}, \, h/\lambda_0 \sim 0.014 \)) using a conductive fabric. The latter was used for a creation of both the ground plane metallization and the top plane radiating patch. The antenna structure was modeled using the IE3D EM simulator (its W/L \sim 0.3 \) and operating frequency is slightly below its half-wavelength resonance). The ground plane dimensions are 165 \times 74 \, \text{mm}, the measured conjugate matched gain of an antenna placed on a human body equals 5.0 dBi. The weight of the antenna is approx. equal to 20 g, it is very flexible and, as it was mentioned before, it is supposed to be integrated into the sportsmen’ number labels.

The comparison of the measured gains of the sample of the meander dipole and the new designed patch antenna is presented in Table 2. The parameter \( b \) represents the distance between the antenna and the phantom used for modeling of a human body (a tank of 5 litres of salt water).

The above-presented values show that the new patch antenna can represent a substantial improvement in the RFID system power budgets according to (2) and (3) (10.7 dB in each of them). The designed patch antenna can also be an appropriate candidate for a RFID antenna that can be fixed directly on large metal objects (containers, cars, etc.).

IV. RFID system optimization

Apart from the design of the new reader and TAG antennas, a number of other simulations and measurements were also performed in order to optimize the UHF RFID system for the identification of sportsmen.
The maximum expected speed of a runner \( v = 10 \text{ m/s} \) provides \( \Delta d_{\text{min}} = 0.142 \text{ m} \), the maximum expected speed of a cyclist \( v = 20 \text{ m/s} \) leads to \( \Delta d_{\text{min}} = 0.285 \text{ m} \). From this point of view, the system optimization must also be focused on ensuring of as high values of \( \Delta d \) with respect to \( \Delta d_{\text{min}} \) as possible. The longer the \( \Delta d \) the higher the probability of correct identification even under more difficult conditions. These negative influences can be described by additional link losses including influence of a more or less random tilt of the TAG antenna caused by a natural tilt of a running human body, and mutual shadowing of runners. Additional link losses were investigated by means of practical measurements. Since it was necessary to measure \( P_{\text{r}\text{TAG}} \) in wide dynamic ranges, a spectrum analyser with a standard \( 50 \Omega \) input impedance was used. Consequently a special test patch antenna with \( 50 \Omega \) output impedance (SMA connector) was designed and used; more detailed description can be found in [2]. All measurements were performed in a distance \( d = 0 \div 10 \text{ m} \) with a step \( 0.2 \text{ m} \) from the finish gate equipped with one reader antenna, see Fig. 9. The gate height was \( h_1 = 3 \text{ m} \), its width \( w_y = 6 \text{ m} \), the measurement TAG antenna was fastened on a breast of a testing person in a height \( h_2 = 1.3 \text{ m} \). In order to map the power distribution also at the border of the finishing corridor area (length \( d \), width \( w_y \), all measurements were performed on the gate axis \( p = 0 \) and also for several off-axis values \( p = 0.5 \div 2.5 \text{ m} \).

For a correct identification, time conditions must also be taken into account. The reader can perform only a definite number (70) of identifications per second. That is why the power budget conditions must be fulfilled for each TAG within a definite range \( \Delta d \). Its minimum value \( \Delta d_{\text{min}} \) can be expressed as:

\[
\Delta d_{\text{min}} = \frac{v}{70}
\]
person standing erectly in a distance of 1 m in front of a person bearing the measurement antenna. Results of these shadowing measurements are presented in Fig. 11. As expected, the additional shadowing loss is strongly dependent on the distance $d$ from the gate base. Within the range $d = 0 \div 3$ m, the influence of the shadowing is negligible. In the range between $d = 3 \div 5$ m, this shadowing loss is up to 3 dB, for $d > 5$ m the shadowing loss is around 6 dB. The measurements show that the additional tilt and the shadowing losses can be very important and must be taken into account. The RFID power budgets must include reserves that are able to compensate for them.

Fig. 11. Influence of shadowing on TAG input power $P_{\text{TAG}}$ $P_t = 35.4$ dBm, $h_1 = 3$ m, $h_2 = 1.3$ m, $\psi = 30^\circ$, $p = 0$ m

![Fig. 11. Influence of shadowing on TAG input power $P_{\text{TAG}}$](image)

(V). Identification reliability tests

In order to verify the behaviour of the optimized system, the identification tests simulating real RFID system appli-

cation were performed. A group of racers moved in the finishing corridor in several different formations, see Fig. 12. In the first formation, 7 racers moved in a row, in the second formation 7 racers formed a kind of a matrix. Each formation moved with 3 different speeds simulating a walk (approx. 4 km/h), a fast walk (approx. 8 km/h) and a run (approx. 15 km/h). In order to eliminate as much random influences as possible, each test was repeated 3 times. The majority of tests were performed with both the new RFID patch antennas and standard planar dipole TAG antennas ($b = 20$ mm).

![Fig. 12. Basic formations of racers used for testing of optimized RFID system a) row, b) matrix](image)

All tests were performed on an asphalt racing course, using the finish gate according to Fig. 9, $P_t = 35.4$ dBm, and $\psi = 30^\circ$. The results of performed tests are presented in Table 3.

<table>
<thead>
<tr>
<th>Configurations of racers</th>
<th>Speed of racers</th>
<th>Percent. of correct identification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dipole</td>
<td>New patch</td>
</tr>
<tr>
<td>row</td>
<td>walk</td>
<td>66.7 %</td>
</tr>
<tr>
<td></td>
<td>fast walk</td>
<td>52.4 %</td>
</tr>
<tr>
<td></td>
<td>run</td>
<td>—</td>
</tr>
<tr>
<td>matrix $p=2.5$ m</td>
<td>walk</td>
<td>61.7 %</td>
</tr>
<tr>
<td></td>
<td>fast walk</td>
<td>52.4 %</td>
</tr>
<tr>
<td></td>
<td>run</td>
<td>—</td>
</tr>
<tr>
<td>matrix $p=0$ m</td>
<td>walk</td>
<td>85.7 %</td>
</tr>
</tbody>
</table>

VI. Conclusion

The crucial objective of this work was to verify the applicability of a standard UHF RFID system for the identification of sportsmen in mass races. The first tests indicated a very low reliability of identification, especially out of the finish gate axis. Therefore, it appeared to be necessary to find and optimise the most sensitive system components. The optimisation was based on the mathematical modeling and a number of practical measurements. It was focused especially on finding of the optimum tilt of the reader antenna and the design of a new reader TAG antenna. The reliability of the optimised system was tested using several configurations of racers and 3 different average speeds.
The results show 100% correct identification in the whole finish corridor area.

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