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

Milan Svanda[1], Milan Polivka[2], Premysl Hudec[3]

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 active 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 Tab. 1 and reference [3], operated in the 869 MHz band for the identification of moving objects (racers 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.

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

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:

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$$L = -20\log\Big(\Big(\frac{\lambda}{4\pi}\Big)\Big|\sqrt{G_{tV}(\alpha_d)}\cdot\sqrt{G_{rV}(\beta_d)}\cdot \sqrt{G_{tH}(\gamma)}\cdot\sqrt{G_{rH}(\delta)}\cdot\frac{1}{r_1}e^{-j\cdot k\cdot r_1}+ \sqrt{G_{tV}(\alpha_r)}\cdot\sqrt{G_{rV}(\beta_r)}\cdot\sqrt{G_{tH}(\gamma)}\cdot \sqrt{G_{rH}(\delta)}\cdot \mathrm{R}(\vartheta)\cdot\frac{1}{r_2}\cdot e^{-j\cdot k\cdot r_2}\Big|\Big) \tag{1}$$

where r_1, r_2 are lengths of direct and reflected rays, $G_rV(\beta)$, $G_rH(\delta)$ stand for angular dependences of the reader antenna gain in vertical and horizontal planes, $G_tV(\alpha)$, $G_tH(\gamma)$ represent angular dependences of the TAG antenna gain in a vertical and horizontal planes, $\bar{R}(\vartheta)$ is a complex reflection coefficient of a wet ground (ϵ_r = 10, σ = 10^{-2} S/m was considered).

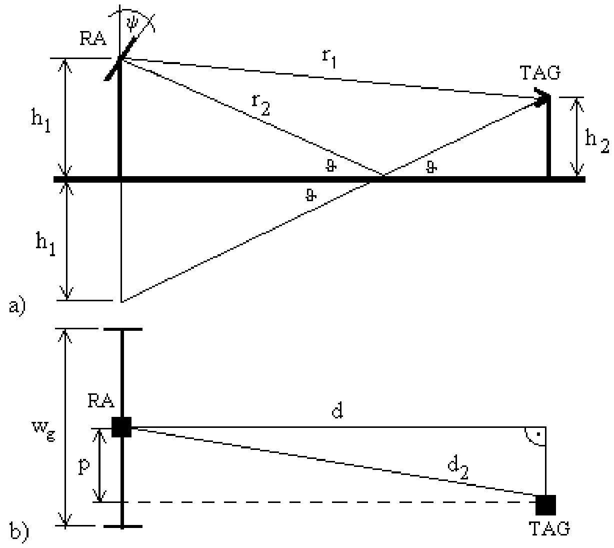

Fig. 1. Configuration of the two-ray model a) side-view b) top-view, with the following parameters: h_1 height of the reader antenna at finish gate, h_2 height of the TAG antenna on a racer's chest, *r1* direct ray trace, r_2 reflected ray trace, d_2 ground plane distance between reader and TAG antennas, w_g width of the finish gate, *p* reader and TAG antenna axis offset

The power received by the TAG antenna P_rTAG in dBm can be expressed as follows:

$$P_{rTAG} = P_t - L - L_f \tag{2}$$

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 $P_{rREADER}$ in dBm can be expressed as follows:

$$P_{rREADER} = P_{rTAG} - L - L_f - L_{conv} \tag{3}$$

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

III. Reader and transponderes antennas

Since the transmitted power Pt and TAG and reader sensitivities are given by the UHF RFID system used, see Tab. 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.

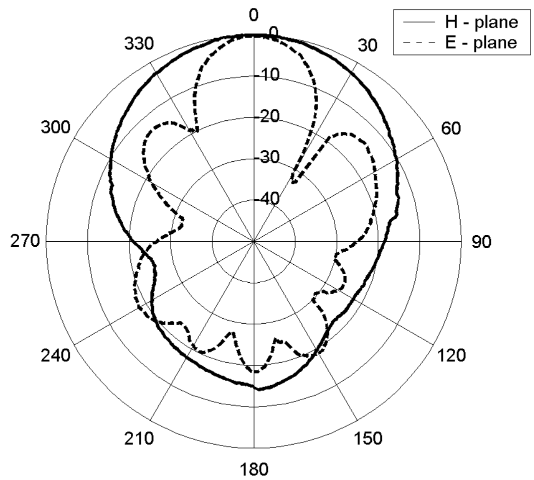

Fig. 2. Measured radiation patterns of designed reader antenna

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 $\times$ 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 meander dipole 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 Tab. 2.

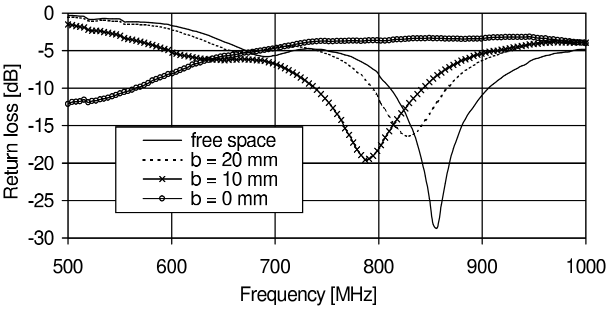

Fig. 3. Planar meander dipole return loss as parameter of distance *b* from human body phantom

Table 2. Measured gain of TAG antennas

Antenna type	G [dBi]
Meander dipole sample, free space	2.2
Meander dipole sample, *b = 20 mm*	-5.72
New patch, free space	6.3
New patch, *b = 20 mm*	5.0

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 and, therefore, at UHF frequencies the patch antennas cannot be extremely small. Secondly, at low frequencies the problems with low antenna efficiency can be expected, see Fig. 4.

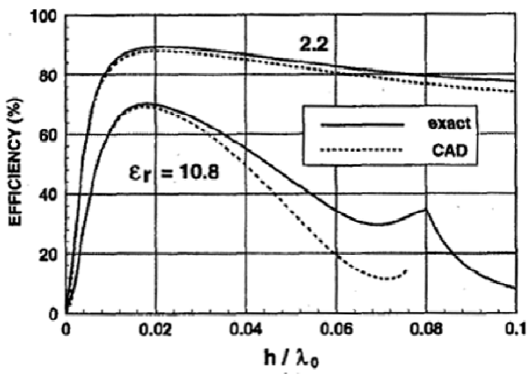

Fig. 4. Radiation efficiency of rectangular patch antenna *W/L* = 1.5 versus relative thickness of substrate, from reference [5]

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 permitivity of an antenna dielectric are used. A very light and flexible foam with and (approx. 4.8 mm) turned out to be a very convenient solution. The TAG antenna is terminated with a chip. Since the chip input impedance is Z_{chip} = 76 - j340 Ω, 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 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 mm, the measured 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.

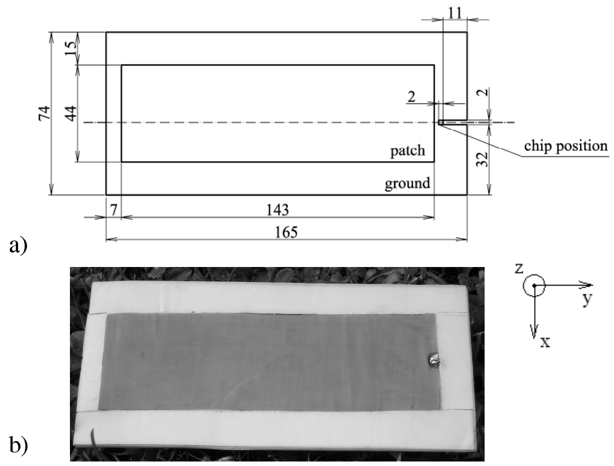

Fig. 5. Transponder patch antenna with chip, a) schematic view, b) photograph of designed prototype

The comparison of the measured gains of the sample of the meander dipole and the new designed patch antenna is presented in Tab. 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.). Fig. 6 shows radiation patterns of the meander dipole antenna measured in free space and on the phantom (normalized to the new patch antenna maximum). Fig. 7 shows radiation patterns of the new patch antenna measured under the same conditions.

IV. RFID system optimization

Apart from the design of the new reader and TAG antennas, a number of other simulations and measurements

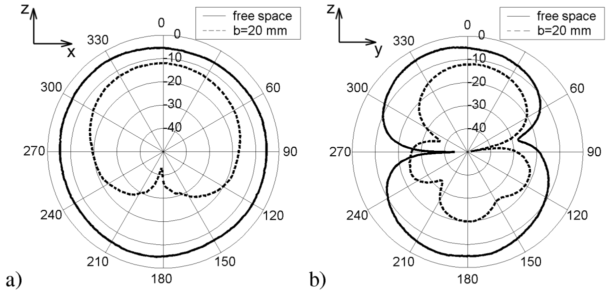

Fig. 6. Measured radiation patterns of meander dipole in free space and in distance *b* in front of human body phantom, a) E-plane, b) H-plane, normalized to maximum of patch antenna radiation pattern

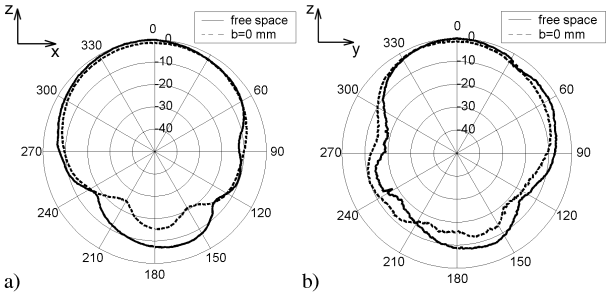

Fig. 7. Measured radiation patterns of patch antenna a) E-plane b) H-plane

were also performed in order to optimize the UHF RFID system for the identification of sportsmen.

The first optimization step was focused on finding the optimum tilt y of the reader antenna, see Fig. 1 a). Fig. 8 shows the simulation of the influence of y on the TAG input power P_{rTAG}. The plot indicates that the optimum tilt is ψ = 30°. Higher y values result in a steep PrTAG decline in the *d* = 3 ÷ 4 m range, whereas lower y value provides a low TAG input power in an important region $d < 4$ m close to the gate, where a smaller influence of shadowing of TAGs by neighbouring sportsmen can be expected.

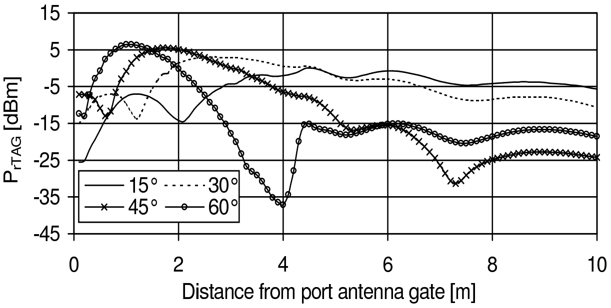

Fig. 8. Measured radiation patterns of patch antenna a) E-plane b) H-plane

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 Δd. Its minimum value $\Delta \mathrm{d}_{min}$ can be expressed as:

$$\Delta d_{\min} = \frac{v}{70} \tag{4}$$

The maximum expected speed of a runner *v* = 10 m/s provides Δd_{min} = 0.142 m, the maximum expected speed of a cyclist *v* = 20 m/s leads to Δd_{min} = 0.285 m. From this point of view, the system optimization must also be focused on ensuring of as high values of Δd with respect to Δd_{min} as possible. The longer the Δd 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_{rTAG} in wide dynamic ranges, a spectrum analyser with a standard 50 Ω input impedance was used. Consequently a special test patch antenna with 50 Ω 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 ÷ 10 m with a step 0.2 m from the finish gate equipped with one reader antenna, see Fig. 9. The gate height was h_1 = 3 m, its width w_g = 6 m, the measurement TAG antenna was fastened on a breast of a testing person in a height h_2 = 1.3 m. In order to map the power distribution also at the border of the finishing corridor area (length *d*, width w_g, all measurements were performed on the gate axis *p* = 0 and also for several off-axis values *p* = 0.5 ÷ 2.5 m.

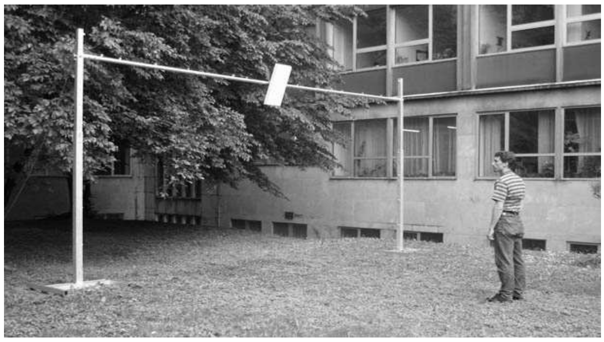

Fig. 9. Race finish gate used for practical measurements

Fig. 10 shows measured P_{rTAG} values as a function of the distance *d* from the gate and tilt of the racer. The presented data indicate that the tilt can result in substantial additional losses, especially in ranges *d* = 0 ÷ 2 m and $d > 7$ m. Nevertheless, in both of these regions the simulated and measured P_{rTAG} values are insufficient even for (erected runner), and the identification is unlikely to be reached here. And on the contrary, the proper identification can be expected in the *d* = 2 ÷ 7 m range, where influence of the tilt is relatively small and the tilt additional loss usually does not exceed 3 dB.

If several runners gather in a small area in a corridor in front of the finish gate, it results in a mutual shadowing and in another type of additional link loss. During the race, nearly infinite configurations of runners can appear.

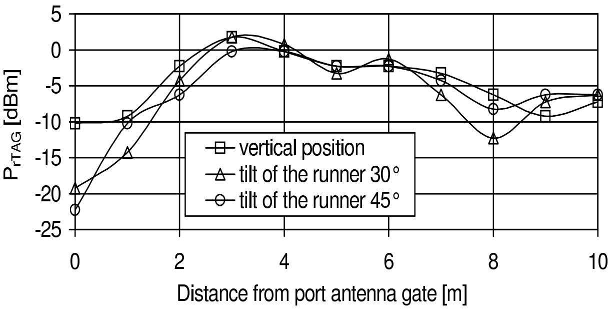

Fig. 10. Influence of tilt of runner y on received TAG power P_{rTAG} (measurement, P_t = 35.4 dBm, h_1 = 3 m, h_2 = 1.3 m, ψ = 30°, p = 0 m

Therefore, it is very difficult to simulate or measure this loss. The basic measurements were performed with one 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. Within the range $d = 0 \div 3$ m, the influence of the shadowing is negligible. In the range between $d = 0 \div 3$ 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.

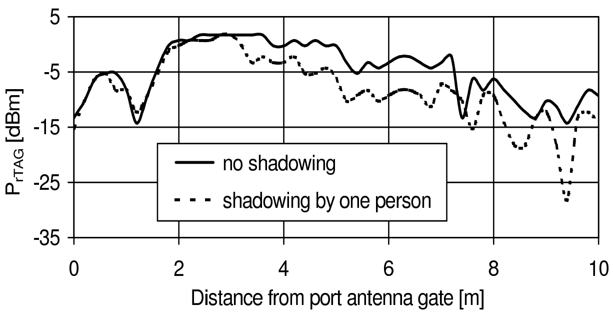

Fig. 11. Influence of shadowing on TAG input power P_{rTAG} P_t = 35.4 dBm, h_1 = 3 m, h_2 = 1.3 m, ψ = 30°, p = 0 m

Fig. 13 depicts a plot of the simulated and measured TAG input power P_{rTAG} at the gate axis p = 0. Fig. 14 shows the simulated and measured P_{rTAG} values at the offset p = 2.5 m - in both cases along with the corresponding sensitivity value. Both figures compare results obtained from the new patch antenna and the meander dipole. All results show that the reader-TAG power budget includes necessary reserve with respect to the TAG chip sensitivity. Fig. 15 shows simulated reader input power $P_{rREADER}$ values with respect to the reader sensitivity. Usage of the meander dipole antenna leads to unacceptably low $P_{rREADER}$ values, especially off-axis. Employment of the new patch antenna can guarantee high enough power even in this return TAG-reader link.

V. Identification reliability tests

In order to verify the behaviour of the optimized system, the identification tests simulating real RFID system application 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).

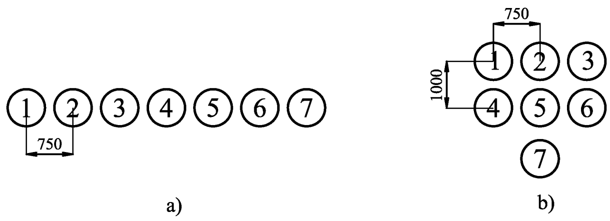

Fig. 12. Basic formations of racers used for testing of optimized RFID system a) row, b) matrix

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

Table 3. Reliability of identification

Configurations of racers	Speed of racers	Percent. of correct identification	
		Dipole	New patch
row	walk	66.7 %	100 %
	fast walk	52.4 %	100 %
	run	—	100 %
matrix p=2.5 m	walk	61.7 %	100 %
	fast walk	52.4 %	100 %
	run	—	100 %
matrix p=0 m	walk	85.7 %	100 %

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

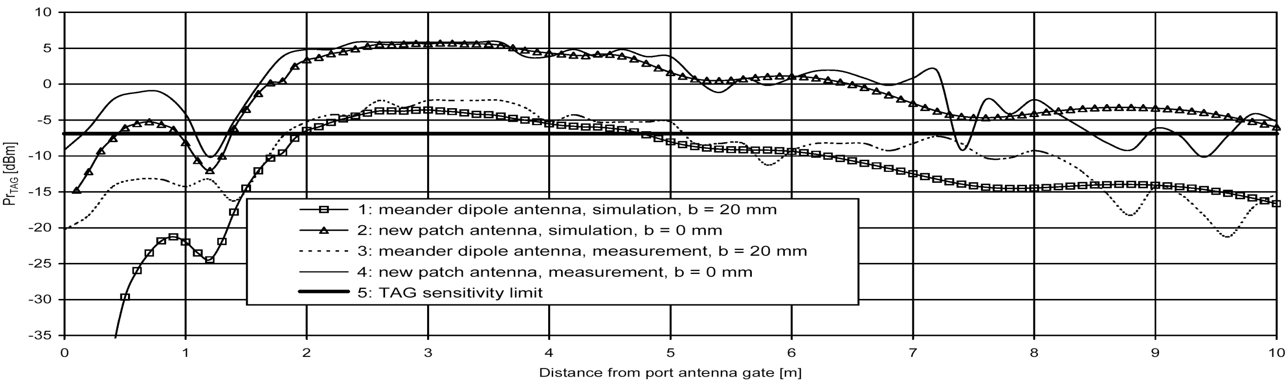

Fig. 13. Simulated and measured TAG input power P_{rTAG} (P_t = 35.4 dBm, h_1 = 3 m, h_2 = 1.3 m, ψ = 30°, p = 0 m)

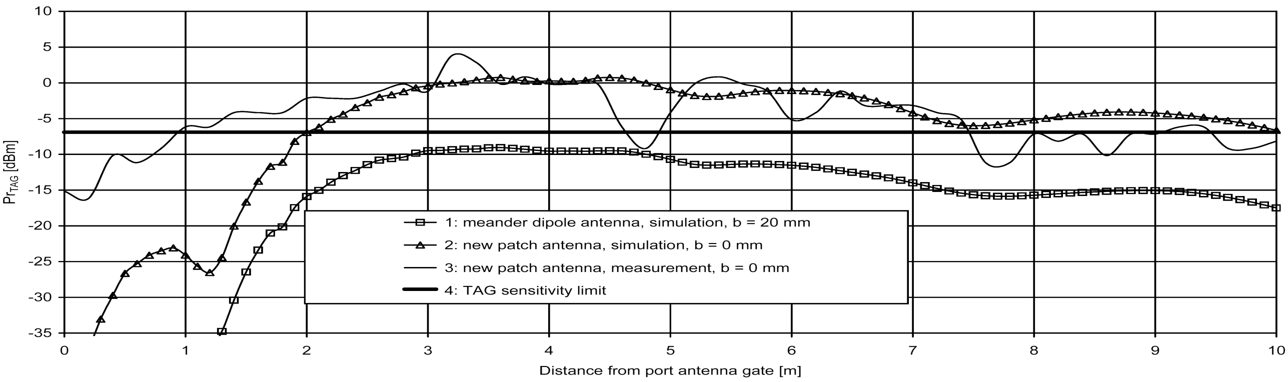

Fig. 14. Simulated and measured TAG input power P_{rTAG} (P_t = 35.4 dBm, h_1 = 3 m, h_2 = 1.3 m, ψ = 30°, p = 2.5 m)

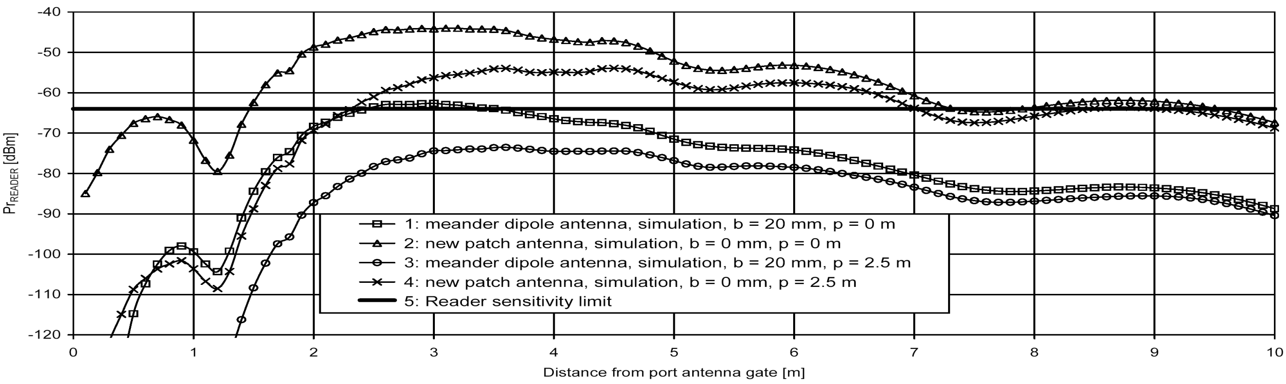

Fig. 15. Simulated and measured TAG input power $P_{rREADER}$ (P_t = 35.4 dBm, h_1 = 3 m, h_2 = 1.3 m, ψ = 30°)

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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