UHF RF Identification of People in Indoor and Open Areas

Milan Polívka, Member, IEEE, Milan Švanda, Student Member, IEEE, Přemysl Hudec, and Stanislav Zvánovec, Member, IEEE

Abstract—The performance of an ultra-high-frequency RF identification (ID) system operating at 869 MHz, intended for the ID of persons in both indoor and open areas, has been validated using the propagation models, as well as the series of practical measurements. A two-ray propagation model and the 3-D ray-tracing model were used for calculations of all important system parameters in open and indoor areas, respectively. For the application mentioned above, a novel (electrically small and, at the same time, low-profile) wearable TAG antenna was designed. It was used in order to carry out the necessary tests as well. The antenna in question is based on an artificial-like surface. The latter provides an important screening effect and avoids detuning. Another virtue of the surface used is represented by the fact that it ensures the minimum loss of the antenna efficiency (resulting from the presence of a nearby human body). The simulations and measurements show that the optimized system can guarantee a reliable ID at distances up to 9 m in open areas and up to 16 m in corridors.

Index Terms—Artificial surface, electrically small antenna, identification (ID) of people, loop antenna, RF identification (RFID) system, TAG antenna.

I. INTRODUCTION

O DATE, given the growing stress put on security aspects, the identification (ID) systems intended for monitoring of people in both indoor and outdoor areas have become increasingly important. The efficient and reliable tracking of the motion of many people in either large buildings or outdoor areas belongs to the relatively difficult tasks. Standard monitoring-ID systems, working in either low-frequency (LF) or high-frequency (HF) bands (125 kHz, 13.56 MHz), which are based on inductive coupling, suffer from a low read distance. This is especially important to reach as high a read distance as possible. To handle the ID process, the person has to, more or less, touch the reader or even insert the ID card into the reader. This requires the installation of relatively narrow gates, where anyone that intends to pass through the gate, is obliged to stop and activate the reader. This kind of ID process is, in general, inconvenient and time consuming. Furthermore, in cases of heavy traffic or multiple accesses, it gives rise to unacceptable time delays.

As a result, RF identification (RFID) systems operating at either ultra-high-frequency (UHF) or microwave frequencies (i.e., at 860–930 MHz or 2.4 GHz) that use electromagnetic wave propagation as a coupling mechanism seem to be more suitable than inductive coupling systems. It is possible to monitor and identify persons at moderate distances, usually over several meters. In addition, the persons that are being monitored are not required to perform any action during the ID process. The monitoring and ID processes do not have any negative repercussions on the fluency of the traffic; in fact, people can even move rather quickly. Such ID systems can be used in manufacturing plants, offices, warehouses, prisons, etc. A specific application of the UHF RFID system, consisting of the ID of sportsmen in mass races, is described in [2].

The performance of any UHF or microwave RFID system is dominantly influenced by the parameters of antennas used and also by the propagation of electromagnetic waves in the intended ID area. This paper is focused on the ID of people in open areas and inside buildings (especially in corridors). The objective is to reach as high a read distance as possible. To handle the RF ID task exactly, the evaluation of the electromagnetic field coverage in the treated area is required.

Usually there is not much space for raising the gain of the reader antennas. High-gain antennas are relatively large and can show too narrow radiation patterns. Due to this, the parameters of TAG antennas are of prime importance. Since their dimensions must be small, while their radiation patterns are required to be wide, it is necessary to optimize their efficiency in order to ensure a long read distance. This is especially important in case of wearable antennas because their parameters can be strongly influenced by the close vicinity of a human body. The new dual-loop antenna designed for the ID of people, presented here, employs a special screening substrate that preserves the acceptable antenna efficiency while guaranteeing a high immunity against the influence of the human body.

The propagation of electromagnetic waves substantially differs in open areas and inside the buildings. In open spaces, it is usually accurate to take into account only the first reflection from the ground. Owing to this, a relatively simple analytical propagation model can be used. On the contrary, in case of indoor applications, the multiple reflections from many walls,
floors, ceilings, windows, doors, and bigger pieces of furniture must be taken into account. In order to provide a satisfactory agreement between the simulation and the practical measurements carried out in corridors, the ray-tracing methods were used in this paper.

II. RF ID SYSTEM DESCRIPTION

A. RF ID System Parameters

The standard commercial RFID system (see Table I) and Trolley Scan\(^1\) were used for the evaluation of the read distance, as well as the reliability of a person’s ID in buildings and open areas.

For the given purposes, it might seem beneficial to use RFID systems operating in the microwave band of 2.45 GHz. This can lead to a considerably easier design of small and efficient antennas. However, the flip side is that the use of the aforementioned frequency results in the propagation loss that is higher by at least 9 dB in both radio paths. The employment of UHF systems for a long-distance ID of people stills represents a very good choice then.

B. Novel TAG Antenna

The degradation of the TAG antenna performance in the close vicinity of a human body belongs to the problems that are to be solved when considering the UHF or microwave RFID of people. The body can be treated as a high-loss dielectric object with a relative permittivity \(\varepsilon_r \sim 50–100\) and a loss tangent \(\tan \delta \sim 0.5–1.2\) [3]. In case of the standard dipole-type TAG antennas, the presence of such dielectric objects causes significant detuning of the antenna and also the absorption of the radiated or received energy [4]–[7]. This results in a low radiation efficiency and, consequently, in a short read distance. Thus, the antenna structures that are immune to the influence of a human body turn out to be advantageous for the intended purposes.

In order to obtain the required immunity, it is, in general, necessary to insert a metallic plate (or a similar screening layer) between the radiation element and the human body. The metallic plate can act as an additional screening plane or can become an inherent part of the antenna structure. The former solution is usually represented by dipole- or loop-type antennas, while the patch antenna and planar inverted F antenna (PIFA) [8], [9] usually represent the latter case. A simple addition of the metallic plane to an antenna structure can lead to a substantial drop in both the antenna impedance and antenna efficiency. In the open literature, several papers, which solve the above-mentioned problem by adding a distance spacer (e.g., [10]–[13]) or by the application of artificial magnetic surfaces (e.g., [14]) have been published.

The application of folded or multiarm-folded dipoles (described in [15]) can be considered as an alternative solution. This approach raises the impedance of the antenna working above the close metallic plane. These structures can provide an extremely low profile (even below the relative wavelength height \(h/\lambda_0 < 0.01\)) and, at the same time, maintain the radiation efficiency on a reasonable level (over 50%). Nevertheless, the relatively large footprint dimensions (comparable to the half-wavelength) can be unsatisfactory for many RFID applications.

The employment of the patch-type antennas, where a metallic ground plane is an inherent part of the antenna structure, represents other possible approach. Nonetheless, it is necessary to take into account that the radiation efficiency of these antennas decreases significantly in case that the height of the substrate is lower than approximately 0.02\(\lambda_0\) [16] (it equals approximately 6–7 mm in the UHF band). For wearable TAG antennas, this height can be unacceptable. The same difficulties can result from the antenna length, which corresponds to a half- or quarter-wavelength (approximately 160–170 or 80–85 mm in the UHF band).

Artificial magnetic surfaces [10] used for constructive summation of the contributions of source and mirror currents to the radiation seem to be suitable for screening carried out near the human body. Nevertheless, due to the necessity to manufacture the shunt inductive components with a height of several millimeters in the UHF band [17], their implementation, to date, does not allow to construct antennas with very low profiles (\(h/\lambda_0 < 0.01\)).

In order to identify people, a novel flat electrically small dual-loop antenna was designed and manufactured (see Fig. 1). It is loaded by a planar array of four sub-wavelength patches that are placed closely over a grounded dielectric slab. A more detailed description can be found in [18]. The patch array is similar to the structure of high-impedance surfaces and suppresses the radiation of mirror currents. This provides a very high immunity against the influence of a nearby human body while preserving the acceptable antenna efficiency (see Table II).

The measured radiation pattern of the loop antenna, fed by the coaxial cable, shows an approximate 15\(^\circ\) tilt that is caused by the nonperfect symmetrization (see Fig. 2). It is not expected that this tilt could be present in case of the TAG antenna-chip connection.

The new antenna is planar; its total size (including the patch array) is equal to 70 \times 105 \times 1.82 \text{ mm} (relative size is 0.2 \times 0.3 \times 0.005\(\lambda_0\) at 869 MHz). The RFID TAGs that have the aforementioned dimensions can be used as standard ID badges.

Table III includes the comparison of dimensions as well as of read ranges of the RFID TAG based on the proposed TAG antenna and other commercially available TAGs, applicable for

---

the ID of people. Indeed, a majority of them are designed for the operation on metal objects. It is obvious that the new TAG provides the longest read range and the lowest TAG height as well. However, the presented data provide only directory information because in the majority of cases, the transmitted powers and the sensitivities of TAG chips and the readers used are unknown. It can be supposed that the transmitted power is 1 W, which corresponds to U.S. regulation ISO 18000-6. It should be emphasized that the recalculation of the read range of the new TABLE III

<table>
<thead>
<tr>
<th>TAG type</th>
<th>TAG dimensions $W \times L \times h$ [mm]</th>
<th>Maximum read range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR80 $^3$</td>
<td>---</td>
<td>3.7</td>
</tr>
<tr>
<td>WF-SM-12 $^3$</td>
<td>125 $\times$ 78.1 $\times$ 9.38</td>
<td>1.2</td>
</tr>
<tr>
<td>WF-SM-13 $^3$</td>
<td>190.6 $\times$ 20.3 $\times$ 17.2</td>
<td>1.8</td>
</tr>
<tr>
<td>WF-SM-14 $^3$</td>
<td>200 $\times$ 162.5 $\times$ 4.69</td>
<td>0.6</td>
</tr>
<tr>
<td>WF-SM-22 $^3$</td>
<td>112.5 $\times$ 28.1 $\times$ 4.69</td>
<td>0.9</td>
</tr>
<tr>
<td>WF-SM-23 $^3$</td>
<td>50 $\times$ 40.6 $\times$ 4.69</td>
<td>0.6</td>
</tr>
<tr>
<td>WF-SM-25 $^3$</td>
<td>150 $\times$ 6.25 $\times$ 6.25</td>
<td>2.7</td>
</tr>
<tr>
<td>WF-SM-26 $^3$</td>
<td>68.8 $\times$ 21.8 $\times$ 4.69</td>
<td>0.2</td>
</tr>
<tr>
<td>WF-SM-28 $^3$</td>
<td>118.8 $\times$ 43.75 $\times$ 7.8</td>
<td>0.9</td>
</tr>
<tr>
<td>WF-SM-40 $^3$</td>
<td>103 $\times$ 31.2 $\times$ 3.1</td>
<td>1.2</td>
</tr>
<tr>
<td>WF-SM-IN03 $^3$</td>
<td>137.5 $\times$ 6.25 $\times$ 6.25</td>
<td>2.7</td>
</tr>
<tr>
<td>WF-SM-SA $^3$</td>
<td>200 $\times$ 175</td>
<td>0.9</td>
</tr>
<tr>
<td>WF-SM-UTS $^3$</td>
<td>175 $\times$ 68.75 $\times$ 18.75</td>
<td>2.4</td>
</tr>
<tr>
<td>UHF metal Tag-01 $^4$</td>
<td>55 $\times$ 20 $\times$ 2</td>
<td>3.0</td>
</tr>
<tr>
<td>UHF metal Tag-02 $^4$</td>
<td>100 $\times$ 18 $\times$ 15</td>
<td>3.0</td>
</tr>
<tr>
<td>UHF metal Tag-03 $^4$</td>
<td>50 $\times$ 40 $\times$ 3</td>
<td>3.0</td>
</tr>
<tr>
<td>UHF metal Tag-06 $^4$</td>
<td>150 $\times$ 18 $\times$ 2</td>
<td>3.0</td>
</tr>
<tr>
<td>Proposed TAG</td>
<td>105 $\times$ 70 $\times$ 1.82 $^3$</td>
<td>4.8 $^1$</td>
</tr>
</tbody>
</table>

1) Read range measured for $P_T = 3.5$ W is 9 m (see Table IV)
2) Height including chip and 2 $\times$ 0.2 mm plastic cover is 2.72 mm.

TAG from $P_T = 3.5$ W (used during tests) to $P_T = 1$ W results in the decrease of the read range from 9 m (measured in the open area) to 4.8 m. On the other hand, the new TAG used during tests is equipped with a relatively less sensitive chip. When using modern chips with the $-14$-dBm sensitivity, the read range can rise up to 10.9 m.

### III. System Power Budgets

As already mentioned, the performance and reliability of the ID depends on the reader-TAG and TAG-reader power budgets. The TAG chip input power $P_{\text{TAG}}$ must exceed the chip sensitivity $P_{\text{TAG min}}$ (i.e., in this case, $-6.9$ dBm)

$$P_{\text{TAG}} \geq P_{\text{TAG min}}.$$  (1)

This condition provides the chip with the energy needed for the modulation of the reflected wave. Accordingly, in order to ensure the correct data processing, the input power $P_{\text{READER}}$
of the reader receiver must be higher than the reader sensitivity $P_{\text{READERmin}}$ (i.e., in this case, $-64$ dBm)

$$P_{\text{READER}} \geq P_{\text{READERmin}}$$

(2)

The power $P_{\text{TAG}}$ in dBm can be expressed as

$$P_{\text{TAG}} = P_t - L - L_f$$

(3)

where $P_t$ is the RF power transmitted by the reader in dBm, $L$ denotes the link loss, and $L_f$ represents the attenuation of the feeder cable in decibels. The peak power of the modulated signal reflected back from the TAG and received by the reader receiver $P_{\text{READER}}$ can be expressed in dBm as follows:

$$P_{\text{READER}} = P_{\text{TAG}} - L - L_f - L_{\text{conv}}$$

(4)

where $L_{\text{conv}}$ is the conversion loss of the chip ($\approx 20$ dB for the used chip). The maximum read distance $d_{\text{max}}$ can be defined as the longest distance $d$, where conditions (1) and (2) are simultaneously fulfilled. In order to evaluate the conditions of the ID in different environments, it is necessary to calculate the corresponding link loss $L$.

A. Open Areas

The propagation of the electromagnetic wave from the reader to the TAG in an open space can be described by the modified two-ray model (see Fig. 3) and [2]. The model involves two paths of electromagnetic waves between the reader and TAG. The first one is formed by a direct ray, whereas the second one is formed by a ray reflected from the ground. The resulting radio link loss can be evaluated by means of the following formula:

$$L = -20 \log\left(\frac{1}{4\pi} \sqrt{G_{\text{rv}}(\alpha_d)G_{\text{rh}}(\beta_d)G_{\text{vh}}(\gamma)G_{\text{vh}}(\delta)} \cdot \frac{1}{r_1} \cdot e^{-j\kappa r_1} + \sqrt{G_{\text{rv}}(\alpha_r)G_{\text{rh}}(\beta_r)G_{\text{vh}}(\gamma)G_{\text{vh}}(\delta)} \cdot R(\beta) \cdot \frac{1}{r_2} \cdot e^{-j\kappa r_2}\right)$$

(5)

where $r_1, r_2$ are the lengths of the direct and reflected rays, $G_{\text{rv}}(\beta)$ and $G_{\text{rh}}(\delta)$ stand for 3-D approximated angular dependencies of the reader antenna gain in the vertical and horizontal planes. $G_{\text{vh}}(\alpha)$ and $G_{\text{vh}}(\gamma)$ represent angular dependencies of the TAG antenna gain in the vertical and horizontal planes, while $R(\beta)$ is a complex reflection coefficient of the ground ($\varepsilon_r = 10, \sigma = 10^{-2}$ S/m were considered).

B. Indoor Areas

The phenomena, which influence the reader-TAG link loss inside the buildings, are substantially more complicated than in the case of the open spaces. Since the electromagnetic waves interact with many surrounding obstacles, multiple reflections and diffractions must be taken into account. Many models and methods, which are applicable for the calculation of the path loss inside the buildings, can be found in the literature (see [19] and [20]).

In the empirical models, approximate mathematical formulas are used for the calculation of the received power. The latter is proportional to the distance from the transmitter $d$ by the term $(1/d)^n$, where $n$ stands for the path-loss exponent that is affected by the geometry, as well as by the electrical properties of the given environment.

In open areas, the value of the path-loss exponent is close to $n = 2$, whereas in corridors, the lower values are reported ($n = 1.4$ in [19]). Thus, in comparison to the case of open areas, substantially longer read distances can be expected in corridors.

On the other hand, the deterministic or semiempirical models [21] utilizing the ray-tracing or ray-launching methods [20] are based on the geometry of the particular task (see Fig. 4) and can provide more precise results. In order to embrace as many propagation phenomena in corridors (with the given dimensions and material parameters) as possible, the 3-D ray-tracing method, implemented in the WinProp program,\(^2\) was used. The aforementioned approach involves up to six reflections and two diffractions from brick walls ($\varepsilon_r = 4, \sigma = 0.005$ S/m), a concrete floor, and ceiling ($\varepsilon_r = 6, \sigma = 0.003$ S/m). The diffractions are calculated by the uniform theory of diffraction (UTD). The results of the performed ray-tracing simulations are presented in Section IV.

Since the ray-tracing method is unable to simulate the return path (TAG-reader) by itself, the calculations of these links are based on the reciprocity and were made using the following formula:

$$P_{\text{READER}} = 2 \cdot P_{\text{TAG}} - L_{\text{conv}} - P_v.$$  

(6)

IV. PRACTICAL MEASUREMENTS

In order to verify the performed simulations, the $P_{\text{TAG}}$ values were measured in several test configurations that correspond to typical scenarios in people ID tasks. Moreover, the values of the maximum read distances $d_{\text{max}}$ were also measured. The RF generator, the test antenna with the same gain as the new TAG antenna, and the spectrum analyzer were used for $P_{\text{TAG}}$ measurements. The new TAG antennas with the connected chip and reader were used for the measurements. The TAG antennas were fixed on a person’s chest at the height of 1.25 m (see Fig. 5).

The measurements were performed in narrow and wide corridors (width of 2 and 4 m, respectively) and in an open area in front of the building. The 4-m-wide corridor has the following parameters: height of 3.35 m, length of 29 m, ended by a wall. The parameters of the 2-m-wide corridor are listed below: height of 3 m, length of 45 m, ended by a glass window. In all the configurations, the standard 8-dBi reader antenna was fixed at a height of 2.5 m with a tilt of $\psi = 30^\circ$. The TAG was attached on a person’s chest at the height of 1.25 m. The transmitted power equaled $P_t = 35.4$ dBm. All values were measured at the axis of the ID area and also for several off-axis offset values.

Since it is very difficult to measure the $P_{\text{-reader}}$ values (i.e., the peak power of the modulated reflected wave at the output of the receiving reader antenna in the presence of a strong nearby $P_t$ power), these values were only simulated. As the link loss $L$ values are identical in (3) and (4) and can be verified from the measurement of $P_{\text{TAG}}$, this attitude seems to be acceptable. Since all plots include the corresponding $P_{\text{TAG,min}}$ and $P_{\text{reader,min}}$ sensitivities, the positive ID can be expected in
Fig. 8. Simulated and measured received power $P_{\text{TAG}}$ versus ground plane distance from reader antenna in 2-m-wide corridor. (a) Antennas axis offset $p = 0$ m. (b) Antennas axis offset $p = 0.8$ m.

Fig. 9. Simulated received power $P_{\text{HEADER}}$ versus ground plane distance from reader antenna in 4-m-wide corridor.

all regions, where the $P_{\text{TAG}}$ and $P_{\text{HEADER}}$ values simultaneously exceed the given sensitivities. The measured $d_{\text{max}}$ values are presented in Table III.

Fig. 6 expresses the simulated (two-ray model) and measured $P_{\text{TAG}}$ values as a function of the distance $d$ from the reader in an open area. The plots show a very good agreement between the simulated and measured values, especially in the most important 2–8-m range. The maximum ID distance is approximately 9 m on axis; both the $P_{\text{TAG}}$ and $P_{\text{HEADER}}$ indicate the difficulties with the reliability of the off-axis ID. For practical implementations, the employment of more suitable reader antennas described in [22] can be recommended.

Fig. 7–10 show the simulated (ray tracing) and measured values of $P_{\text{TAG}}$ and $P_{\text{HEADER}}$ in 4- and 2-m-wide corridors. The agreement is acceptable because the majority of differences can be explained only by the estimated parameters of walls, their heterogeneities and reflections from the metal door and window frames, which were not included in the model. Nevertheless, it was observed that these influences had no essential impact on the ID distance of the RFID system. The measured $d_{\text{max}}$ values are presented in Table IV.

The implementation of every particular UHF RFID system has to be focused on the most sensitive components of the system. In case of the monitoring of people at moderate distances, this principle particularly concerns TAG antennas. The applicable TAG antenna should show small dimensions, exhibit a high immunity against the influence of a nearby human body and also provide a high antenna efficiency. For these purposes, a new dual-loop TAG antenna, loaded by a planar array of four sub-wavelength patches, was designed and manufactured.

The calculations of the read distance in open areas were performed using an analytical two-ray model. Similar calculations for indoor corridors were carried out using a 3-D ray-tracing method. All simulations were verified by a series of practical measurements. The presented plots show very good agreement between the calculated and measured results. The presented UHF RFID system exhibits 9-m read distance in open areas and up to 16 m in the narrower corridor.

A definite number of readers, placed in suitable positions, are able to ensure a reliable monitoring and ID of people moving in a building or the surrounding areas. Such a system can be applicable for various access systems.

V. CONCLUSION

<table>
<thead>
<tr>
<th>Test configurations</th>
<th>Read range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prediction</td>
</tr>
<tr>
<td></td>
<td>reader- TAG sim.</td>
</tr>
<tr>
<td>Open area</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Cor. 4 m</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
</tr>
<tr>
<td>Cor. 2 m</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
</tr>
</tbody>
</table>

*) small margin of 0.8 dB over chip sensitivity does not allow the reliable RFID system performance
ACKNOWLEDGMENT

This study has been undertaken at the Department of Electromagnetic Field, Czech Technical University, Prague, Czech Republic.

REFERENCES


Polívka et al.: UHF RFID People in Indoor and Outdoor Areas

Milan Polívka (M'04) received the M.Sc. and Ph.D. degree in radioelectronics from the Czech Technical University, Prague, Czech Republic, in 1996 and 2003, respectively. He is currently with the Department of Electromagnetic Fields, Czech Technical University, as an Assistant Professor. He has authored or coauthored over 60 scientific publications, including one book chapter and four utility models. He holds two patents. His research interests are focused on the field of the design of planar multibands, electrically small RFID and gain enhanced antennas, and application of artificial electromagnetic materials in the antenna field.

Dr. Polívka is a chair of the Microwave Theory and Techniques (MTT)/Antennas and Propagation (AP)/Electronics (ED)/Electromagnetic Compatibility (EMC) joint section of the Czech–Slovak Chapter of IEEE since 2007.

Milan Švanda (S’08) received the M.Sc. degree from the Czech Technical University, Prague, Czech Republic, in 2007, and is currently working toward the Ph.D. degree in electromagnetic fields at the Czech Technical University.

His main research activities are aimed at the study of new materials in antenna technology. His other research interests are linked to the field of antennas, RFID, and metamaterials.

Přemysl Hudec received the M.Sc. and Ph.D. degree in radio electronics from the Czech Technical University, Prague, Czech Republic, in 1982 and 1995, respectively.

In 1982, he joined the Department of Electromagnetic Fields, Czech Technical University. His research activities include the design of microwave circuits and microwave measurement devices. In recent years, he has focused on microwave defense and security systems.

Stanislav Zváňovec (S’03–M’05) received the M.Sc. and Ph.D. degrees from the Czech Technical University, Prague, Czech Republic, in 2002 and 2006, respectively.

He is currently an Assistant with the Department of Electromagnetic Fields, Czech Technical University. His current research interests include electromagnetic wave propagation issues for millimeter-wave and quasi-optical and optical systems and UWB radio propagation channels.