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Reliability of active RFID tag immersed in water for anti-rapt applications

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Abstract— In this paper, a method is developed to evaluate the reliability of active RFID tags immersed in water. This situation exists in particular when infants wearing anti-kidnaping tag take bath. This study discusses the effects on the electromagnetic radiation of an emitting tag plunged into a water volume and then proposes a statistical method to predict the radio coverage of the immersed tag. Finally it demonstrates that the RFID technology is barely affected by this issue even though other RFID technologies do not support immersion.

Keywords— *RFID localization; radio propagation; indoor environment.*

1 INTRODUCTION

To prevent abduction for infant, technology based on RFID is a growing application. To control where and when infant is in the maternity ward, RFID tags are attached to infant's ankle and are identified and located by stations installed in the building. Several technologies or strategies have been proposed to detect and locate the RFID tags. The first strategy consists in measuring the RSSI of the ID signal sent by the tag regularly (e.g. every quarter of minute) and deducing infant's positions by RSSI triangulation [1]. Another strategy uses the Time Of Flight (TOF) triangulation usually based on UWB signal [2]. A third strategy is called polling LF-RF: the tag sends its ID through a radiofrequency (RF) link only if it is in the vicinity of a station placed closed to an access door which covers a limited range by a low frequency (LF) signal. Technologies with passive tags and security gate are affected by weaker ranges than technologies based on active tag.

One of the limits of technologies based only on RF links is due to the immersion of the tag in water, for example during a bath. The degradation of the RF link can result in false triggering of alarms which discredits the system. The proposed study discusses about the impact of immersion of an active RFID tags based on a RF-LF link. A statistical method is proposed to predict the radio coverage of RFID detection and control if the deployment of stations is efficient.

2 PRESENTATION OF THE ANTI-RAPT SYSTEM

2.1 Functional principle of the system

Provide abduction is a hands free access control application. Fig. 1 describes the operation of the system. Stations which are placed near access doors of secured areas emit permanently a low frequency (LF) signal at 125 KHz. The strength of the emitted signal

is adjustable to cover a detection area ranging from 1 to 3 meters. When a tag enters in a detection area, it sends its ID to the station with a RF signal in the UHF band. In our application, 434 and 908 MHz ISM frequencies are used. The access is blocked and alarms are sent if unauthorized persons arrive in a forbidden area. The low power consumption of tag, the exactness of the detection area and the weak influence of the site configuration on the installation parameters are the main advantages of this technology.

Compared to usual hands free access control applications, some changes are provided:

- Tags are attached with wristband because they have to be carried all time.
- A permanent RF link between the tag and the station is reused. It sends warning if the wristbands is wrenched or if the battery level is low, whatever the tag location. Further, RF polling is sent every fifteen minutes to ensure that the tag is working effectively fine.

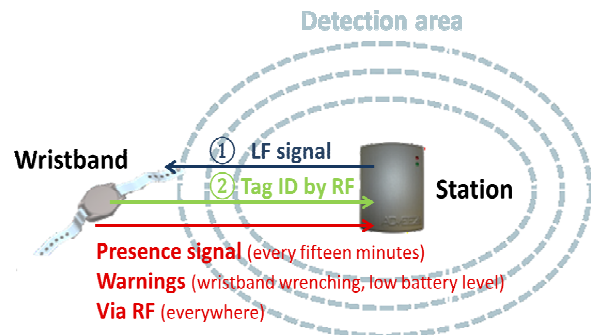


Fig. 1. Functional principle of the anti-rapt system

2.2 Limitations

It is unlikely that a bath is situated in detection area of a station. Therefore reliability of LF signal is ruled out in this study. The immersion of the tag may be harmful for the RF range. Limitations of the RF range can be caused by desensitization and delay spread. As the throughput is about 20kbits/s, delay spread is rejected. Desensitization of links depends on two main parameters:

- The radiated power emitted by tags. This parameter is affected by tag immersion.
- The sensitivity of station and the ambient noise, which is supposed constant and receiving antennas are also supposed quasi omnidirectional.

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3 EFFECT OF THE IMMERSION ON AN RFID TAG

The bathtub is considered as a parallelepiped filled with water. The volume of water is equivalent to a dielectric resonator. The tag antenna can excite some of the cavity modes of the dielectric resonator. The resonant frequencies of cavity modes are given by equation (1) [3]:

$$\vartheta = \frac{c}{2\sqrt{\epsilon_r}} \sqrt{\frac{m^2}{a^2} + \frac{n^2}{b^2} + \frac{p^2}{c^2}} \quad (1)$$

Where (m,n,p) are the mode number and (a,b,c) the dimensions of the bathtub. The relative electric permittivity ϵ_r of water is about 72 and depends on temperature and frequency [4]. The high electric permittivity value induces high reflection amount at dielectric boundaries. It enhances the dielectric resonator behavior of the volume of water. Although the radiation diagram of the tag is similar to the radiation pattern of a magnetic dipole, the bathtub resonances give rise to a complex field distribution around the volume of water. Electromagnetic simulation with FEKO© [5] are performed in order to study this field distribution.

The volume of water is a dielectric parallelepiped, with a relative permittivity and an electrical conductivity equal to 72 and $650\mu\text{S/m}$ respectively. It is representative of bath water at 37°C . Tag antenna is modeled by an equivalent magnetic dipole with a magnetic moment equal to $7.54e-6 \text{ A.m}^2$. A cylindrical empty volume enwraps this source. The whole is placed within the water volume.

To illustrate the influence of immersion on the radiated field, 2D far field patterns at 908 MHz in various situations are compared in Fig. 2. The first curve is the reference case without water and the two other cases are the immersion; only the position of the tag inside the volume is changed.

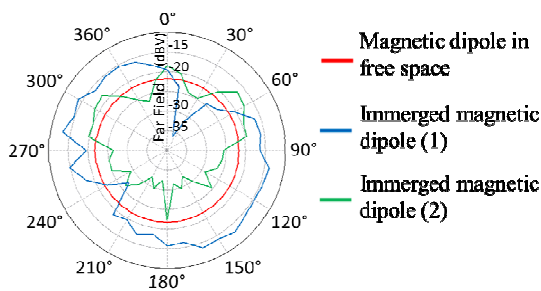


Fig. 2. Farfield on level water at 908 MHz

Depending on the frequency, the dimensions of the bathtub, the orientation and the position of the tag within the bathtub and the electrical characteristic of the water, the variation of the far-field radiation in a given direction can exceed 20dB, without any obvious relation between the far-field emission and these parameters. This complex behavior has been confirmed by radiated measurements of an immersed tag in anechoic chamber.

The bathtubs can have different size and baby's tag can be placed everywhere inside this volume. Since these parameters are unknown, and as they can influence the radiated emission strongly, a stochastic approach is the best solution to study the impact of the tag's immersion.

4 STOCHASTIC DISTRIBUTION OF THE ELECTRIC FIELD RADIATED BY AN IMMERSED TAG

4.1 Methodology of probabilistic approach

The field radiated by the immersed tag cannot be precisely determined since the dimensions of the bathtub, the position and the orientation of the tag remain unknown. However, if these parameters are considered as random variables, the statistical distribution of the field radiated by the tag can be established. This distribution will be integrated to the indoor radio propagation model presented in part V in order to predict the effect of immersion on the tag radio coverage. A comparison with the radio coverage of a non-immersed tag will allow evaluate the degradation due to the tag immersion.

The method consists to simulate a large sample with different values of unknown parameters from the electromagnetic model presented in the previous part. Results are the radiated electric field in all directions from the tag emission frequency (434 and 908 MHz). 3645 simulations are performed in about 4 days on a machine equipped with an Intel® Pentium® Dual CPU 1,80GHz processor. Post-processing is then applied to extract the statistical distribution of the electric field radiated by the immersed tag

4.2 Cumulative distribution of the radiated emission of tag

In order to highlight the significant impact of the immersion on the RF link strength fluctuations, the distributions of electric field radiated by a tag immersed in water or placed in free space are compared. The statistical distribution of the electric field in this last case can be computed analytically. The electric field produced by a magnetic dipole in far field at a distance R is given by (2) [6].

$$E = E_0 * \sin(\theta) * \frac{e^{-j\beta_0 R}}{R} = E_{far}(\theta) * \frac{e^{-j\beta_0 R}}{R} \quad (2)$$

With E_0 which depends on the amplitude of the excitation and the size of the magnetic dipole. E_{far} is the normalized amplitude of the electric field. It does not depend on the distance R but is influenced by the dipole orientation which is unknown. Theoretically, the distribution of the electric field radiated by the magnetic dipole in all directions is given by the following cumulative distribution function (CDF).

$$F_{E_{far free}}(E_{far}) = 1 - \sqrt{1 - \left(\frac{E_{far}}{E_0}\right)^2} \quad (3)$$

The simulation results of the magnetic dipole immersion for various water volume dimensions, tag position and orientation give the distributions of the

electric field F_{far} at 434 and 908 MHz, as shown in Fig 3. Their CDF can be approximated by a Rayleigh distribution, as suggested in [3] to model field distribution in reverberation chambers.

$$F_{E_{\text{far}}_{\text{immerse}}}(E_{\text{far}}) = 1 - e^{-\left(\frac{E_{\text{far}} - \epsilon}{2\sigma^2}\right)^2} \quad (4)$$

An offset ϵ is added to obtain a representative model. The parameters of the distribution are given in Table I at 434 and 908 MHz.

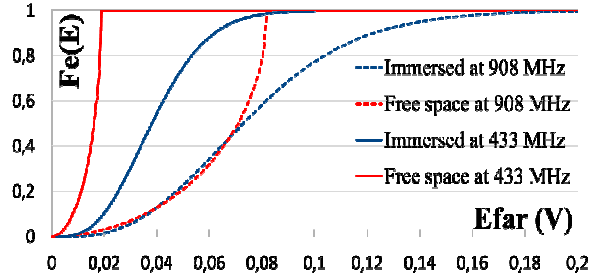


Fig. 3. Comparison between CDF of magnetic dipole in free space and immersed in water

At 434 MHz, the amplitude of the electric field E_{far} radiated by the magnetic dipole is larger than the field produced by the same dipole in free space conditions. This result shows that the RF coverage will be always better in these conditions when the tag is immersed. However that is not the case at 908 MHz

TABLE I. PARAMETERS OF CUMULATIVE DISTRIBUTION FUNCTIONS

Frequencies	E_0 (V)	σ (V)	ϵ (V)
434 MHz	0,0187	0,0250	0,0084
908 MHz	0,0819	0,0522	0,0115

5 PROPAGATION MODEL

5.1 Radio planning solver

The solver is based on the Multi-Resolution Frequency Domain ParFlow (MR-FDPF) method [7]. The starting point of this algorithm is a ParFlow approach proposed by Chopard and al. [8]. The advantages of the method are its speed and its accuracy. Attenuation, reflection and diffraction phenomena are modeled. Radio coverage at 434 MHz over a 1500 square meter building floor can be obtained in only 3 seconds on a machine equipped with an Intel® Core™ I3 clocked at 2,53GHz.

As the coverage is computed only in a 2D plane, the study will be limited to a building floor. Building models are easy to construct: the positions of the walls and their reflectance and absorption coefficients of its wall are requested in input. The input data of the solver are the building map, the emitter positions and the wall properties. These parameters are determined from the electric permittivity and loss tangent of regular building materials. The solver computes the radiated power density and the propagation loss L_p within the structure.

5.2 Validity of model

To verify the exactness of the results given by the radio propagation solver, on-site measurements have been completed and compared with simulation results. The measurements of the received electric field are performed with a calibrated handheld RF field strength meter in the different rooms of the installation site.

Simulated results are interpolated to fit with the grid of measurement points. The differences between the measured and simulated propagation loss are evaluated. Fig. 4 presents a comparison between the measured and the simulated propagation losses along a corridor. This model of loss propagation in indoor environment is validated with a correlation factor of 0,947.

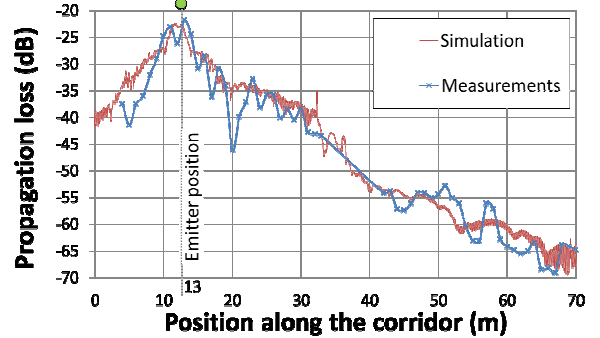


Fig. 4. Comparison between the measurement and simulation of the propagation loss along a corridor at 908 MHz

6 STATISTICAL DISTRIBUTION OF THE RADIO COVERAGE

The statistical distributions of the tag far field radiation determined in part IV are introduced in the radio planning solver to determine a statistical distribution of the radio coverage of a tag within a building. A comparison between the coverage of an immersed and a non-immersed tag is provided in order to evaluate the impact of the immersion on the risk of RF link loss.

6.1 Integration of the CDF of the radiated emission of the tag

The aim of the radio planning solver is to evaluate the probability that a RF link can be established between a tag and a receiving station, i.e. that the signal to noise ratio of the received signal is beyond a given threshold. In other word, a RF link is lost if the propagation loss exceeds a threshold noted $L_{p_{\text{max}}}$.

In part IV, the CDF of the electric field radiated by a tag have been established. However, they cannot be exploited from the radio planning solver results directly since they are given in term of propagation loss. It is necessary to convert the CDF of the radiated electric field into the CDF of propagation loss. The propagation loss can be computed according to equation (5):

$$Lp = \frac{P_r}{P_t * G_t * G_r} \quad (5)$$

With: - Lp , loss propagation determined by MR-FDPF
 - P_r is the sensitivity threshold of station and G_r the gain of receiving antenna
 - P_t and G_t are the transmitted power and the antenna gain of the tag. In far field, they are linked to the electric field by (6)

$$E_{far} = \sqrt{K * P_t * G_t} \quad (6)$$

When, K is equal to 60 for the isotropic antenna. The probability of RF link loss is given by the complementary CDF of the propagation loss F_{Lp} .

$$F_{Lp}(Lp) = 1 - F_{E_{far}} \left(\sqrt{\frac{P_r * K}{Lp * G_r}} \right) \quad (7)$$

Other statistical parameters can be used (body influence, attenuation of crowd, different environment noise, jamming ...) but they are disregarded here.

6.2 Results of statistical coverage

The radio planning solver provides predictions of the average propagation loss within the building. The CDF of the immersed tag and the tag in free space are used to compute the probability that the propagation loss exceeds the maximum allowed propagation loss on each point of the building. Fig. 5 presents the coverage map for both tag configurations. Only one station is placed, at the green point.

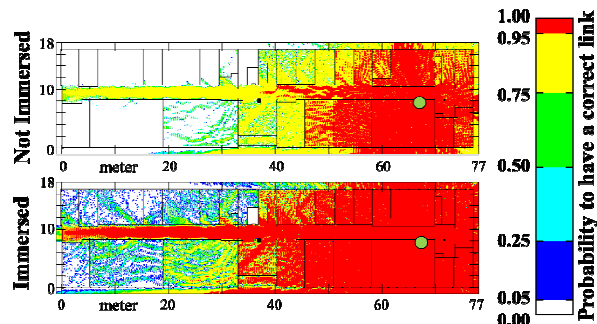


Fig. 5. Comparison of the RF coverage between a non-immersed and an immersed tag at 434 MHz.

In accordance with previous results, the coverage is really better when the tag is immersed at 434MHz, as shown in Fig. 6. In this case, the probability that the RF link establishes correctly exceeds 95 % over 60 % of the building surface. When the tag is not immersed, this area falls down to 48 %. At 908 MHz differences are less significant, in accordance with Fig 3.

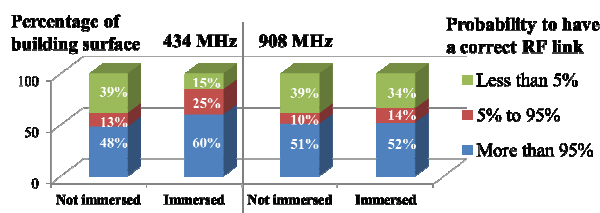


Fig. 6. Percentage of building correctly covered

Therefore, our anti-kidnapping system reliability is not degraded by the immersion of the tag. However, this conclusion depends on the detection strategy implemented in the RFID system. Technologies based on RSSI triangulation are degraded since depending on the tag orientation the emitted radiated field emission has a strongly random level and the localization becomes imprecise.

7 CONCLUSION

The study aims to discuss about the impact of the immersion of a RFID tag dedicated to an anti-kidnapping application. These systems based on different technologies have to be reliable in any event, for example immersion in water during baths.

The emitted radiated field by an immersed tag is affected randomly since the bathtub behaves as a resonant cavity. A stochastic method is the best approach to study the influence of the immersion of the tag. From many simulations, an expression of the statistical distribution of the electric field radiated by the immersed tag has been determined, and introduced in a radio planning solver to determine the effect of immersion on the radio coverage. The obtained results have shown that it is unlikely that the present and warning signals transmitted by the emitted tag are attenuated completely at 434 and 908 MHz. The immersion should not degrade the reliability of our RF-LF detection technology. Nevertheless, technologies based on RSSI triangulation are affected by this random variation of the emitted radiated field. The localization becomes inaccurate and the risk of false triggering of alarms increases. To study the reliability of the immersion of an UWB tag, the method proposed in this paper must be upgraded to take into account the timing characteristics of the RF channel. However the approach shown here remains valid.

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