Study of the Readability of Passive UHF RFID Tags Placed Inside a Cargo Van by a Reader Located Outside

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Original scientific paper

***Abstract*: The aim of this paper is to study the feasibility of getting information from a cargo van returning back on its storage area by using a low cost communication system. According to the low speed of the vehicle and to the involved short distances, a UHF RFID solution is considered. An experimental study shows that passive tags may be read successfully but not in the entire space of the van. A semi-empirical numerical method based on the Geometrical Optics is derived in order to build a fast computer aided-positioning tool that may help to optimize the location of the tags. The same software tool is used for carrying out a parametric study that informs on the best antenna system to use. It is find out that a solution using passive tags and two antennas limits the theoretical results to 90% successful reading percentage whereas using semi-passive tags ensures a 100% one in the whole space of the vehicle.**

***Index Terms*: Attenuation, Readability, UHF RFID, Vehicle.**

I. INTRODUCTION

The UHF RFID technology is originally dedicated to identification of tagged products or objects placed directly in front of a reader several meters away. Associated to a sensor, RFID tags may also transmit more relevant information such as temperature, pressure, acceleration or merely detect the presence of an object. Thus, RFID technology is more and more used in the Structural Health Monitoring (SHM) in order to monitor deformations of bridges for instance. In a similar manner, one can now imagine new applications of RFID in the domain of the Maintenance, Repair and Operation (MRO). This paper presents a work that focuses on a RFID future system that may monitor the health of subsystems embedded inside a vehicle. For example, one can expect to get the level of a car wash water tank, to check the presence of an important security equipment within a bus (ex: extinguisher) or to monitor the default in a lightning fluorescent tube within a train carriage. The information is required only when the vehicle returns back on a storage area. Many work have been achieved that deal with intra-car communications [1-5] but the system considered in this paper should be more cost-effective and less invasive if a unique reader is placed outside the whole vehicles to manage. However, it remains to study the feasibility of reading tags inside a vehicle with that reader. From the electromagnetic point of view, the bodywork of the vehicle acts like a metallic enclosure with apertures. We consider the case of a reader located outside the vehicle. Once penetrated inside the vehicle, high frequency waves propagate by multipath. In order to characterize the propagation effects, the most accurate method is the experimental one. Unfortunately, it will be uneasy and expensive to carry out such experiments with costly laboratory measurement equipment in every kinds of existing vehicle in the World.

Moreover, practical implementation of such a future automatic maintenance or detection system will take advantage of the existence of a computer aided positioning tool. Therefore, the objective of our work has been to build a modelling software allowing to give relevant information with a minimum computing time. According to these constraints, we developed a software tool based on a Modified Geometrical Optics method (MGO). Actually, this method is a sort of trade-off between the Geometrical Optics (GO) and the Uniform Theory of Diffraction (UTD). It has been previously used with success for studying the radiation of WLAN signal from inside toward outside of a train at 2.4 GHz [6]. The developed numerical software tool is very fast but its semi-empirical nature requires calibrating it with measurements. Actually, the aim of those measurements is to provide the suitable attenuation value that gives the best results when used with the model. Various measurements have been carried out by authors like Ouyang and Chappell in enclosed reflective structures [7], Hill and Kneisel for mobile networks [8], Kostanic and al. [9] as Kiani and al. [10], Gustafsson and al. [11] for the per-window transmission issue. For information, the study of a miniature antenna sprayed over the body of a cargo van [12] gives 20 dB of in-out attenuation, closed to the value find in the present work.

The modelling method is described in section II. Results of measurement made with a commercial UHF RFID reader are given in section III. A detailed analysis of the phenomena encountered in the application case is provided in section IVThe conclusion gives recommendations for reading successfully passive tags in a slow moving van using a fixed outside placed reader. Results obtained with semi-passive tags are also given.

II. A MODIFIED GEOMETRICAL OPTICS METHOD

The feasibility of reading tags placed within a vehicle by using a reader located outside requires studying the amount of

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energy that reaches those tags by multipath propagation. In order to search the reader antenna system that provides the best reading rate reachable in various vehicles, many experiments have to be considered but are too time consuming. A numerical modelling tool is well-suited to achieve a wider parametrical study in many geometrical configurations. Such a tool would be also used by integrators in charge of the installation of a fleet maintenance system based on the RFID technology. In the past, attempts have been made to model the radiation of high frequency electromagnetic waves from inside toward outside of vehicles. In 2002 and for a frequency of 314 MHz, a dozen of hours of computing time was needed for gaining the results described in [13]. A model simply based on the Geometrical Optics Theory does not take into account the diffraction phenomena which exist although their effects are moderately important [14]. The Uniform Theory of Diffraction should be adequate but, unfortunately, addition of the diffracted rays results in an increase of the computing time, inconsistent with the expected fast running software tool. Harrysson in [15] proposed to assess the contribution of the diffracted rays by using a simplified formula defined previously by Berg in [16]. However, this solution is still too difficult to apply and another idea has been investigated: a Modified version of the Geometrical Optics called MGO. This new approach simulates the diffraction effects by using transmitted rays that propagate through virtual materials constituting the obstructing objects. In our case, these objects are polygonal planes which model the body of the vehicles. Assuming not perfect conductive thin planes, transmitted rays carrying few energy equivalent to the diffracted energy may enter into the vehicle according to [17] and [18]. A lossy slab is characterized by a complex permittivity ε_r* and its loss tangent tgδ respectively given by formulas (1) and (2) where σ is the conductivity, ω the pulsation and ε_0 the free space dielectric constant. The quantities ε_r' and ε_r" are respectively the real and imaginary part of ε_r*.

$$\varepsilon_r^* = \varepsilon_r - j\frac{\sigma}{\omega\varepsilon_0} = \varepsilon_r' - j\varepsilon_r'' \qquad (1)$$

$$tg\delta = \frac{\sigma}{\omega\varepsilon_0\varepsilon_r} = \frac{\varepsilon_r''}{\varepsilon_r'} \qquad (2)$$

Fig. 1 shows the trajectory of a ray through a plane parallel slab of thickness d made with a lossy medium 2 surrounded by a purely dielectric medium 1 (air). The magnetic permeability of free space noted μ_0 is taken for each medium. According to the polarization, Transverse Magnetic (TM) and Transverse Electric (TE) modes will be considered. The former is characterized by a magnetic field orthogonal to the incident plane whereas the latter is characterized by an electric field orthogonal to the same plane. Angles θ_i and θ_r define respectively the angle of the incident ray and of the refracted rays. Owing to the numerical values taken for the physical parameters considered in this case, it is admitted that both angles are equal.

Transmission and reflection coefficients are given by formulas (3) to (6). Multiple transmission coefficient is given by formula (7) where subscripts ij means the direction from medium i toward medium j and conversely.

According to the fact that the thickness of the slab is much smaller than the wavelength and that the expected equivalent transmitted rays are not due to the multiple reflections inside the slab, it is assumed that the equivalent transmission coefficient is simply given by the product $T_{12}T_{21}$ for each polarization. Formula (8) gives the equivalent complex permittivity which characterizes an equivalent material constituting the polygonal planes constitutive of the vehicles. The propagation factor k_t is given by formula (9).

$$R_{TM} = \frac{\varepsilon_r^* \cos\theta_i - \sqrt{\varepsilon_r^* - \sin^2\theta_i}}{\varepsilon_r^* \cos\theta_i + \sqrt{\varepsilon_r^* - \sin^2\theta_i}} \qquad (3)$$

$$R_{TE} = \frac{\cos\theta_i - \sqrt{\varepsilon_r^* - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon_r^* - \sin^2\theta_i}} \qquad (4)$$

$$T_{TM} = \frac{2\cos\theta_i\sqrt{\varepsilon_r^*}}{\varepsilon_r^* \cos\theta_i + \sqrt{\varepsilon_r^* - \sin^2\theta_i}} \qquad (5)$$

$$T_{TE} = \frac{2\cos\theta_i}{\cos\theta_i + \sqrt{\varepsilon_r^* - \sin^2\theta_i}} \qquad (6)$$

$$T_{slab} = \frac{T_{12}.T_{21}.e^{(-jk_t d)}}{1 - R_{21}^2.e^{(-jk_t d)}} \qquad (7)$$

$$\varepsilon_{r\,equ}^* = \varepsilon_{requ} - j\frac{\sigma_{equ}}{\omega\varepsilon_0} \qquad (8)$$

$$k_t = \omega\sqrt{\mu_0\varepsilon_{requ}^*\varepsilon_0} \qquad (9)$$

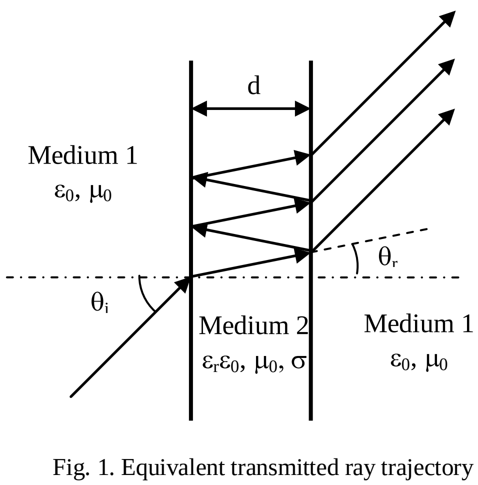
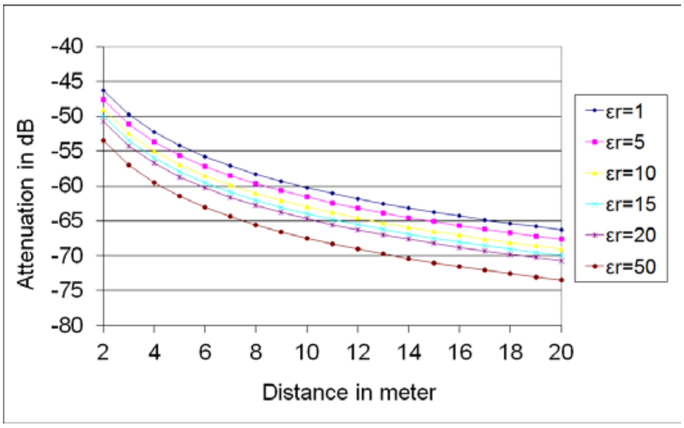
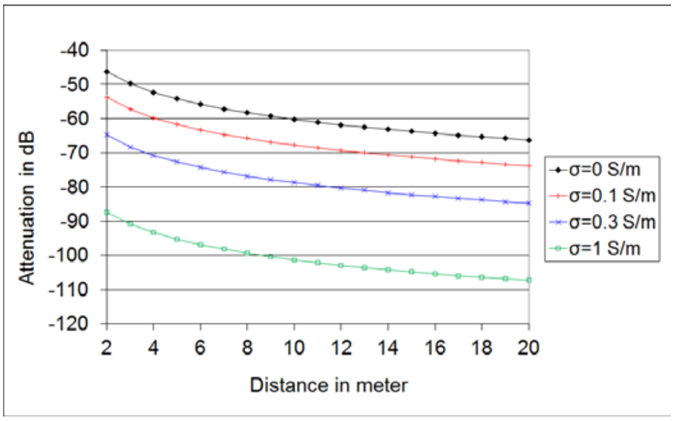


Fig. 1. Equivalent transmitted ray trajectory trough a parallel lossy slab

The value of the equivalent parameters has to be chosen in order to produce amplitude of the transmitted field equivalent to the diffracted one. It will be shown later in this text that this value will be estimated through preliminary experiments during a calibration step. It is possible to use either the equivalent relative permittivity or the equivalent conductivity to achieve this task. A parametric study has been made in order to define the behavior of the equivalent transmission coefficient T_{slab} versus those two parameters. Curves in Fig. 2-a- show the attenuation of the transmitted power through a dielectric slab versus the distance using a source located 1m in front of the slab and for 6 values of the permittivity ε_{requ}: 1, 5, 10, 15, 20 and 50. The effect of the coefficient T_{slab} is given by the difference of the offset value between each curve. Curves of Fig. 2-b- show the same results for 4 values of the conductivity σ_{equ}: 0, 0.1, 0.3 and 1 S/m in the case of a lossy dielectric slab with ε_{requ}=1. In both cases, the reference level is defined by the free space with conductivity equal to 0 S/m and a relative permittivity equal to 1.



2-a-



2-b-

Fig 2. Attenuation of a thin slab versus the distance
-a- Dielectric material (σ=0S/m)
-b- Lossy dielectric material (ε_r=1)

In order to take into account a wide range of attenuation values accounting for various types of vehicles, the conductivity is the most suitable parameter to retain. Nevertheless, the chosen value of the permittivity is an equivalent value of a complicated structure and may be different of the value of any known physical material.

III. Experimental study of the readability of RFID tags inside a cargo van with a reader located outside

Fig. 3-a- shows a cargo van built with lateral metallic panels. The vehicle includes a windshield and lateral windows at the front and windows on the rear doors. It is expected to transmit RF energy through these apertures made with glass. The Intelleflex bistatic reader FMR 6000 shown in Fig. 3-b- has been used. It was equipped with a dual patch antenna 8dBic of gain. The transmitted power was equal to 30 dBm leading to an isotropic equivalent radiation power (EIRP) of 35 dBm according to the linear polarization of the tags antenna. The principle of the experiment is to place tags in different locations within the van and the reader outside 1m away. The main beam of the reader antenna points in a direction orthogonal to the moving axis of the vehicle. The readability of each tag is defined by a binary value (read or not read) during the travelling of the van at a 10 km/h speed. It matches with the case of a vehicle that returns back on a park area or into a garage. UPM Raflatac Dogbone passive tags also shown in Fig. 3-b- have been used. Those tags match with the standard EPC Global Class1 Gen2 and run particularly well at European RF frequency range (865 MHz – 868 MHz) owing to their datasheet. The maximum reading distance in free space reaches 9 meters in perfect propagation conditions.

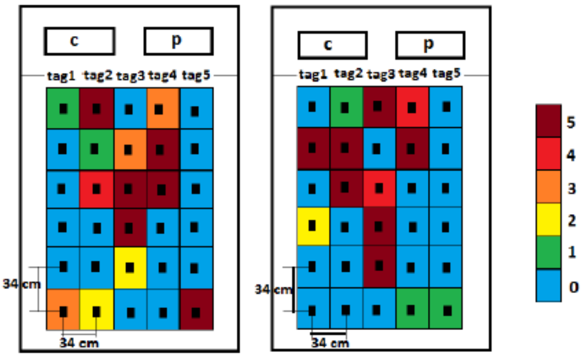
-a-

-b-

Fig 3. Experimental setup
-a- View of the cargo van
-b- View of the antenna, the tag and the reader

Tags have been placed within the body of the empty van on a 34 cm x 34 cm grid at 50 cm height equal to the height of the outside reader antenna. They are put on a cardboard with the main axis of their antenna parallel to the axis of the vehicle. Actually, 5 tags have been aligned on a line and displaced line by line during the experiment. The distance between tags has been chosen according to the results of Choi and al. [19] who studied the impact factors of tag to tag interferences as well as Dobkin in [20].

Fig. 4 shows the results obtained with two different positions of the reader: on the driver side (cartography at left) and on the passenger side (cartography at right). It has to be noticed that the driver is unavoidable and attenuates the RF energy incoming into the vehicle. The van has travelled 5 times for both locations of the reader antenna. The number of successful reading has been reported with different colors. Blue color highlights the cases of no reading. Squares colored in dark red show that purely passive tags should be read successfully and regularly in some locations especially in the middle of the vehicle. Difficulties appear when tags approach the walls but not under a distance equal to the wavelength in order to avoid the mismatch effect due to neighboring conductive materials.



-a- -b-

Fig. 4. Number of successful reading tags within a cargo van
-a- : reader on the driver side
-b- : reader on the passenger side

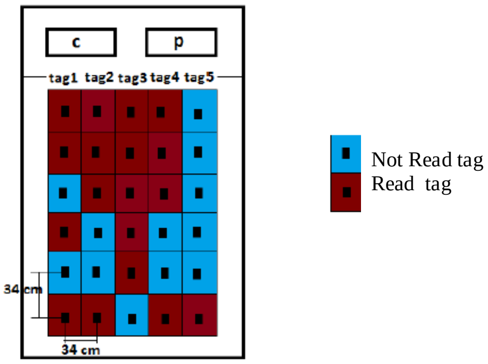


Fig. 5. Cumulative results of 5 travels of the vehicle in front of 2 reader antennas placed on each side (driver and passenger)

Fig. 5 shows the cumulative readability results obtained for the total 5 travels and 2 antennas placed on either side of the van. Tags located on blue squares can never be read whereas tags on red squares can be reached at least once by the reader during the travelling. It is clearly brought out that the RF energy comes from the dielectric parts of the vehicle located at the front and at the rear. Furthermore, the spatial diversity brings a gain but not enough to ensure the successful reading of the whole number of passive tags that is limited to 60 %.

IV. Numerical Study of the Readability of RFID Tags Inside a Cargo Van with a Reader Located Outside

A numerical model of the van is described in Fig. 6. The body of the vehicle is 3.9 m long, 1.7 m wide and 1.8m high. A preliminary calibration step made with the result of measurements carried out with a continuous wave (CW) RF source at 868 MHz gives an attenuation value equal to about 25 dB from outside to inside. The equivalent conductivity, in the MGO sense, of the faces forming the metallic parts of the vehicle numerical model has been fixed to 16 S/m. The relative permittivity of the glass faces forming the windows is equal to 5 and is based on an estimated value of the attenuation of 3dB.

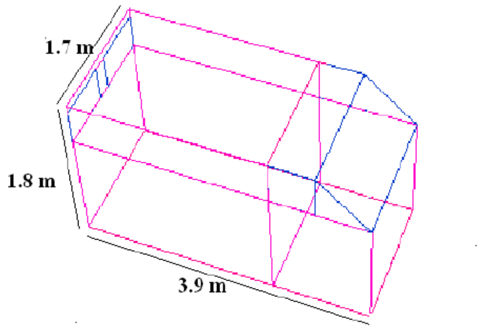


Fig. 6. Definition of a numerical model of a cargo van

The numerical model based on the MGO described in section II uses a unique source point that radiates as a Hertzian omnidirectional dipole having a gain equal to 1.76 dBi. In this work, the dipole orientation is parallel to the axis of the vehicle, horizontal versus the ground plane. A convergence study has been made in order to limit at 4 the number of reflections on the multiple polygonal planes. The readability of a tag placed at one point of the grid (read or not read) is defined by the value of the received power versus -15 dBm considered as a typical passive tag threshold value. The displacement of the vehicle is simulated considering 11 locations of the reader regularly distributed along the length of the vehicle as indicated in Fig. 7.

Variations of the attenuation of the received power amplitude are given in figure 8 versus the positions of the reader for 3 points A, B and C located within the vehicle. Taking into account the transmit power, the gain of the antenna and the threshold of -15 dBm, the admissible attenuation power is equal to -50 dBm. One can see in Fig. 8-a and 8-c that the received power level passes above the threshold required for the reading on a distance of about 75 cm. It takes 270 ms to the vehicle travelling such a distance at a speed of 10 km/h, large enough to achieve the reading protocol and get the Electronic Product Code of tens of tags taking safety margins [20]. A tag placed at the point B cannot be read for any relative position of the van versus the reader. Figure 8-d shows the same result obtained at each point without the vehicle. The tag is always read in that free space case according to the distances which are less than 5 meters. The maximum values are reached in front of the reader whereas in presence of the vehicle, it is reached for the most distant reader locations. Indeed, this case allows to rays coming from the distant reader antenna to enter the vehicle by the windshield situated at the right of the rectangle drawn in Fig. 7.

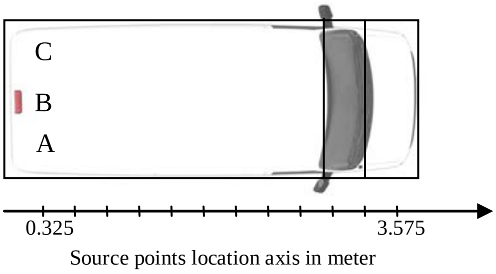


Fig. 7. Locations of the reader and 3 reception points A, B, C

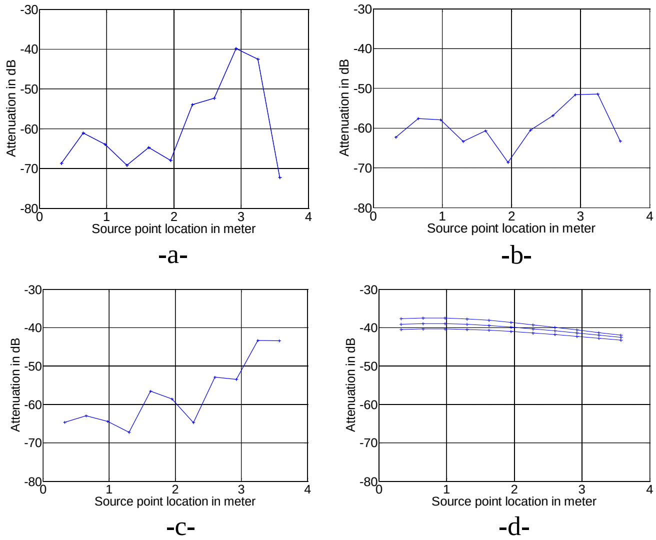


Fig. 8. Variations of the received power amplitude computed at points A, B, C of the van (a, b, c) and without the van (d)

The principle of the numerical study is to compute the received power on 69 x 157 points distributed on a horizontal rectangular grid filling a horizontal layer of the van. Fig. 9 shows examples of results computed with a reader antenna height equal to 40 cm similar to the height of the reception grid. Yellow points indicate that the tag is read whereas green points indicate a failed reading. Cartography of Fig. 9-a- has been obtained with a unique reader antenna located at the 6th transmitted point, namely at the middle of the vehicle (x = 1.95 m). Two sectors can be roughly distinguished according to the effect of the tridimensional structure of the vehicle. The modelling does not take into account any driver. Therefore, use of 2 antennas placed on either side of the van gives a complementary result gained by symmetry and presented in Fig. 9-b-. Such a diversity gain is highlighted by Dimitriou in a similar study of the readability of UHF RFID tags within the room of a hospital [21].

The percentage of successful reading is greatly increased when considering the case of a reader antenna located close to the front of the vehicle since it eases radiated energy to get through the front lateral windows. The computed result has been reported in Fig. 10-a- with the same color code and resolution of Fig. 9.

Finally, the better result is acquired summing the results of the eleven cartographies as displayed in Fig. 10-b-. The total successful reading rate reaches 90 %.

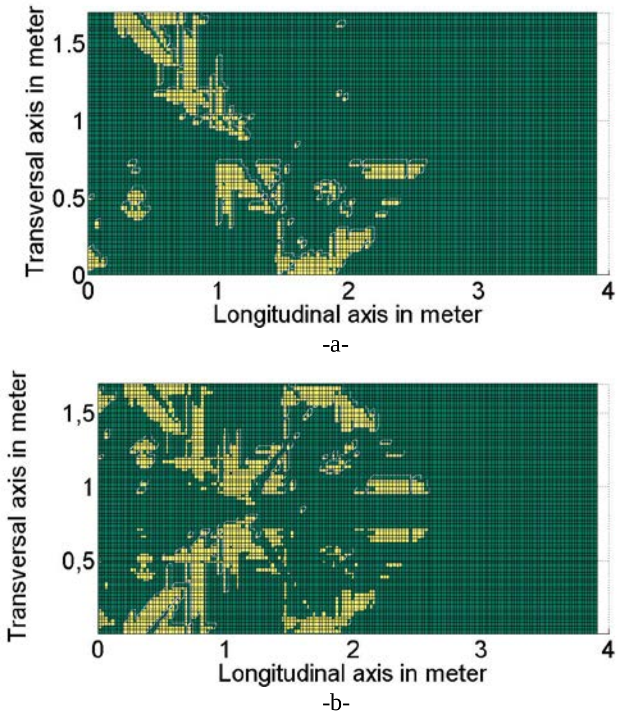


Fig. 9. Readability of a passive tag located within a cargo van;
Yellow: Successful reading – Green: unsuccessful reading
-a-: 1 antenna on one side of the van at x = 1.95 m
-b-: 2 antennas on either side of the van at x = 1.95 m

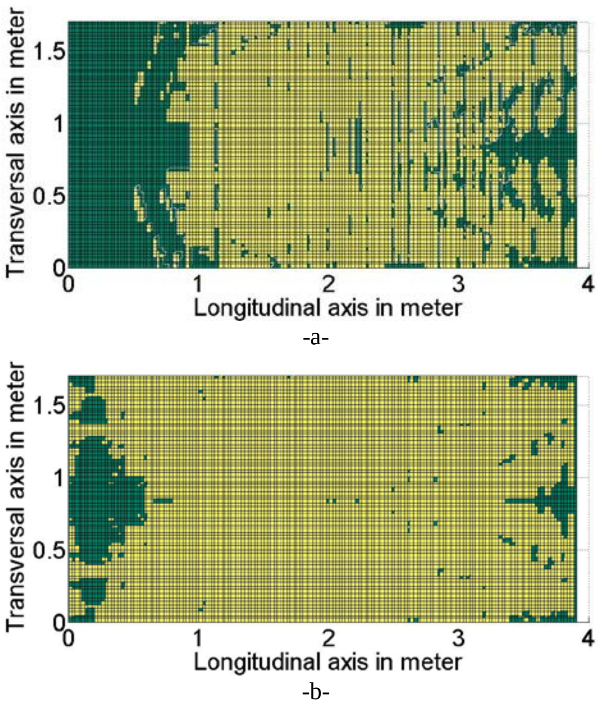
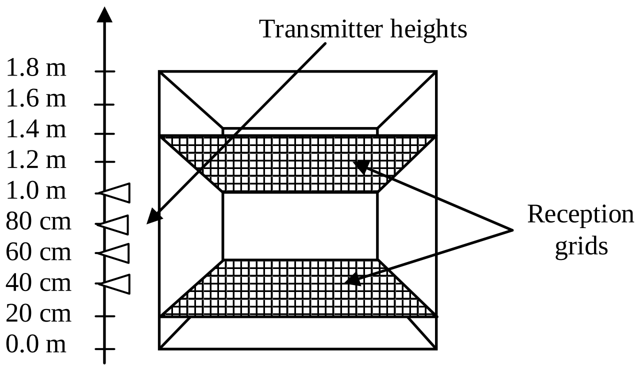


Fig. 10. Readability of a passive tag located within a cargo van with an outside reader antenna pointed out toward the front lateral windows at a height of 40cm above the bottom of the vehicle body;
Yellow: Successful reading – Green: unsuccessful reading
-a- with 1 location of the reader at x = 3.25 m
-b- with 11 locations of the reader along the x axis

In a second step, one has been interested in the effect of the relative height between the reader and tags. For a single horizontal location of the reader (x = 1.95 m), 4 heights have been tested (40 cm, 60 cm, 80 cm and 1 m) with 2 reception grid heights : 20 cm and 1.40 m. Those geometrical configurations are detailed in Fig. 11. Successful reading percentages are less than those given before because of the unique location of the reader, but it is pointed out once again that diversity of location on either side of the van is helpful. Tags located on the upper reception grid (1.40 m) seem to be more difficult to be read successfully. This phenomenon is likely due to a lower containment of the space in this case, i.e few rays can link the source point to the tag point.



Rear view of the van numerical model

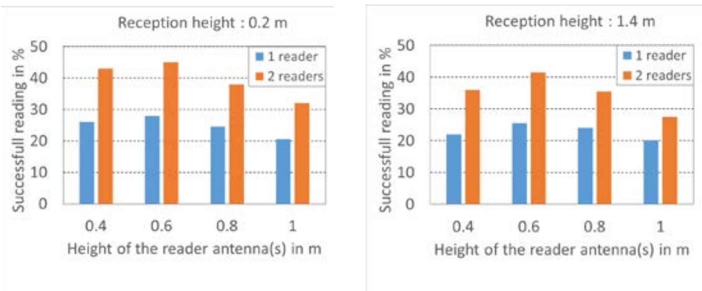


Fig. 11. Study of the effect of the relative heights between inside tags and one or two outside reader(s)

V. CONCLUSION

This paper demonstrates that reading of purely passive EPC C1G2 tags placed inside a cargo van with a reader located outside is feasible but not easy. The worst case is obtained for a stopped vehicle near by a reader located in front of the metallic part of it. Less than 50% tags may be read in that case. However, successful reading rate may reach around 90% when the vehicle travels at a low speed of about 10 km/h and using 2 antennas placed on either side. Better results may be obtained using 2 supplementary antennas placed on either height upper and lower. Unfortunately, those results are given by a simple numerical model based on a Modified Geometrical Optics method which is, right now, a little bit optimistic. The future work consists in moderating the reading rate, for instance, with a penalty gain as introduced by other authors who take into account the effect of the neighbor environment around the tags [22]. Another solution is to use Battery Assisted Passive tags (BAP) having a weaker sensitivity threshold of about -20 dBm to -40 dBm. We also used such tags (STT-8000 Intelleflex) with a compatible reader of the same brand in order to check that 100 % of them exhibit a successful reading in every location inside the cargo van. However, this solution requires using more expensive and cumbersome tags.

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