Progress In Electromagnetics Research B, Vol. 27, 101–126, 2011

DETECTION OF MASSIVE NUMBERS OF DVDS BY A UHF RFID SYSTEM

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Abstract—This paper aims to provide an effective solution to the problem of detecting a large number of densely stacked DVDs. The number is in the range of 2000. In order to achieve that goal, firstly the structure and the properties of materials comprising a DVD disc and a DVD case are investigated. The effect of the metal layer in the disc on the interrogating wave is evaluated via theoretical analysis and simulation. Based on that analysis and simulation, and on numerous experiments on either a single labeled DVD in free space or multiple labeled DVD in a DVD stack, two solutions are proposed whereby over 95% DVDs in a great portion of a 2000 DVD stack could be detected. Eliminating the tags which have weak performance, the percentage can be 100%. This paper not only expands the range of categories detectable by UHF RFID systems but also provides a process and method for item-level tagging in which the number of the items is in the range of thousands.

1. INTRODUCTION

RFID is a type of automatic identification technology making use of radio waves. UHF RFID systems are the RFID systems operating at ultra high frequency band which is around 1 GHz for RFID applications. Significant work has been done on the reader [1, 2] and tag design [3]. This paper aims to detect a large number of DVDs in a stack by UHF RFID systems. The large number considered here is in the range of 2000. The identification of each packaged DVD film, consisting of a DVD case with a DVD disc inside, among a large number of packaged DVD films in a stack is required by industry, especially by the retail industry. A single DVD film is easily detected

Received 22 July 2010, Accepted 24 November 2010, Scheduled 29 November 2010
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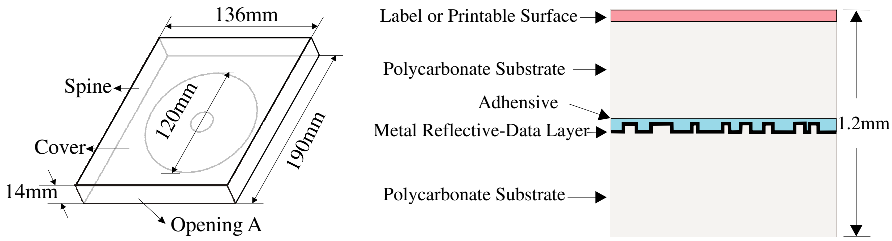
by a barcode system. However, when a large number of packaged DVD films are densely piled up into a stack, the cost in time to scan them one by one makes the barcode system totaly impractical for addressing this task. UHF RFID systems are employed to solve this problem because of the radio wave's penetrability. However, DVD discs contain a very thin metal layer (30 nm) working as a reflective layer of a laser beam. The existence of the metal layer will vary the tag antenna impedance [4] which is intentionally designed to be conjugate matched to the connected chip impedance. The impedance mismatch will degrade the performance of the tag [3, 5]. Moreover, when a large number of packaged DVD films are piled up into a stack, the wave reflection, attenuation, absorption and diffraction occurring in the stack should be taken into account as path loss [6]. Some work about the DVD/CD detection by using of UHF RFID systems has been done [7]. The number of DVD/CD discs those studies intend to detect is within the range of 20, when a much larger number of packaged DVD films are closely piled up into a stack, those studies are not suitable to address this problem of detecting each film in the stack. This paper aims to provide an original solution to detect a large number in the range of 2000 of DVDs densely stacked. One thing that should be noted here is that "DVD" is meant to reference a DVD-ROM (Read Only Memory).

The outline of this paper is as follows. Section 2 introduces the physical and electrical parameters of a common packaged DVD. In Section 3, the effect on a uniform plane wave of a thin metal film in the DVD disc is studied by means of theoretical analysis and simulation. In Section 4, the tag labeling method was investigated by deriving the reading range of a labeled DVD in free space experimentally. Three testing schemes were selected for further study. In Section 5, the three testing schemes are further examined by conducting experiments in a DVD stack. Section 6 extends the experiments in Section 5 by expanding the number of labeled DVDs and adopting a more practical testing environment. Finally, in the last section, conclusions are drawn.

2. PARAMETERS OF A PACKAGED DVD FILM PRODUCT

In this section, the physical parameters and electrical parameters of a regular packaged DVD film are given. As mentioned above, a packaged DVD film is composed of a case and a disc. The dimensions of a regular DVD case are shown in Figure 1(a). Generally, DVD cases are composed of polypropylene which is a plastic material with low dielectric constant and low loss [8]. For the further discussion, two



(a) A regular DVD case (b) Disc cross view [10]

Figure 1. The structure of a regular packaged DVD film product.

faces visible from the angle shown in the figure are named as cover and opening A respectively, and one face invisible from this angle is named as spine. The cross section in Figure 1(b) is what we are concerned about. The whole thickness of the optical disc is 1.2 mm. The data layer takes the form of a grooved metal reflective layer. The thickness of the reflective metal layer is about 30 nm [9]. The metal material is usually aluminium or aluminium alloy.

As seen in the structure shown in Figure 1, the polycarbonate makes up majority of the disc. Grosvenor et al. [11] reported the dielectric constant of this material is about 2.88 with low loss around 1GHz. Besides polycarbonate, DVD discs consist of some very thin layers, as shown in Figure 1(b). Since all except the metal layer are dielectrics and very thin compared with the wavelength of UHF RFID frequency band, they are neglected. The theoretical and simulation analysis of this thin metal layer in the DVDs is discussed in the next section.

3. THEORETICAL ANALYSIS AND SIMULATION OF THE EFFECT ON A UNIFORM PLANE WAVE OF A THIN METAL FILM

3.1. Theoretical Analysis

A thin metal film here is meant to be a film of which the thickness is much less than the skin depth. The aluminium layer thickness in a DVD is only 30nm much less than the skin depth at the UHF RFID operating frequency. The surface resistance R_s of a metal material can be derived by (1).

$$R_s = \rho/t \tag{1}$$

where t is the thickness of the metal. ρ is the electrical resistivity of one metal material viz. aluminum, is 28.2 nΩm. For the aluminium

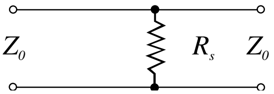


Figure 2. Transmission line model.

layer in a DVD, the surface resistance derived by (1) is $0.94\,\Omega$.

The case when a uniform plane wave is perpendicularly incident on an infinite 30 nm aluminium film can be analyzed by a transmission line model, as shown in Figure 2, in which the surface resistance of this aluminium film is placed in shunt across the line. The reflection coefficient of the 30nm aluminium layer can be calculated by inserting the surface resistance of the 30 nm aluminium layer R_s and the wave impedance of free space $Z_0 = 377\,\Omega$ into (2). The reflection coefficient Γ derived is -0.995, which means there is a large amount of reflection occurring at the aluminium film. Both the small surface resistance and large (in magnitude) reflection coefficient indicate that this thin aluminium film will still perform effectively as a metal layer which is much thicker than the skin depth. It is concluded that an incident wave in which the electric field is tangential to the thin aluminium film will not propagate well along its propagation direction when the wave meets the aluminium film, but an incident wave in which the electric field is perpendicular to the thin film can propagate well.

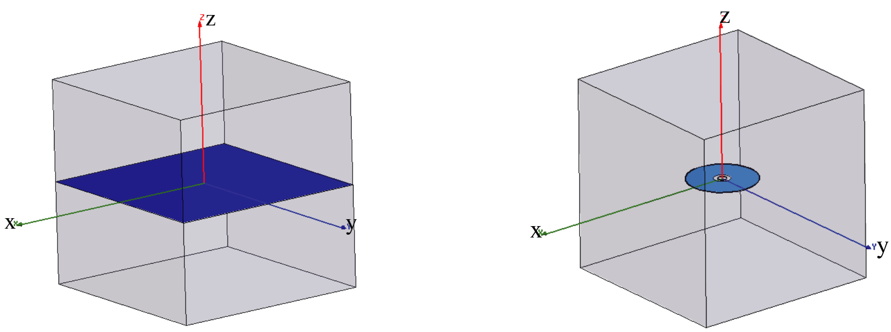
$$\Gamma = \frac{R_s \| Z_0 - Z_0}{R_s \| Z_0 + Z_0} \tag{2}$$

3.2. Simulation on Single Disc

The above theoretical analysis has also been verified by the simulation software Ansoft HFSS. A cube radiation boundary is built in a coordinate system as shown in Figure 3(a) in which the cube length is 325 mm (the wavelength of 923 MHz wave in free space), the cube center is set to be origin of the coordinate system. The material inside the cube is set to be vacuum. The radiation boundary here works as the boundary allowing the wave inside to pass through the boundary and radiate infinitely far away from that surface. A square of which the length is the same as the cube length and of which the centre is also at the origin of the coordinate system is modeled on the xy plane. The boundary condition of this square is assigned to be a 30 nm aluminium layer. Three forms of uniform plane waves at 923 MHz are added in a 81.25 mm distance (one quarter wavelength) above the square respectively. The three forms of incident wave are

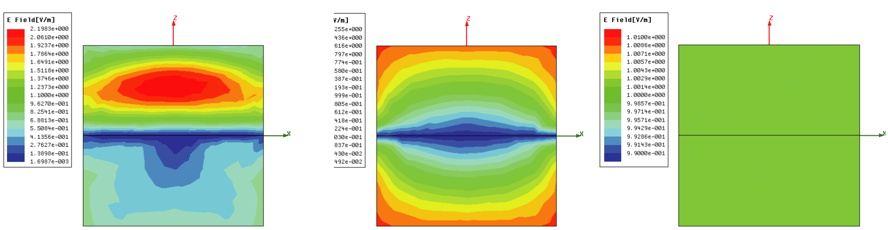
1) propagating direction k is perpendicular to the film and electric field E_i is tangential to the film, $k = (0, 0, -1)$, $E_i = (1, 0, 0)$; 2) both propagating direction k and electric field E_i are tangential to the film, $k = (0, 1, 0)$, $E_i = (1, 0, 0)$; and 3) propagating direction k is tangential to the film and electric field E_i is perpendicular to the film, $k = (0, 1, 0)$, $E_i = (0, 0, -1)$. After the simulation processing, the magnitude of r.m.s phasor of the total electric field (incident field plus scattered field) distribution in the xz plane at 923 MHz are shown in Figure 4. The reason why the fields is observed at 923 MHz is because the frequency is the center frequency of UHF RFID band in Australia.

According to Figure 4(a), it is found that most of the incident wave cannot penetrate the aluminium film, instead it is reflected. That is the reason why the magnitude of the electric field is nearly zero on the surface of the film and it is doubled in a quarter wavelength above the film. Figure 4(b) indicates that the wave can propagate well if it is far away from the film, however, when it gets close to



(a) The square aluminium film (b) The aluminium film in the disc

Figure 3. Two simulation models.



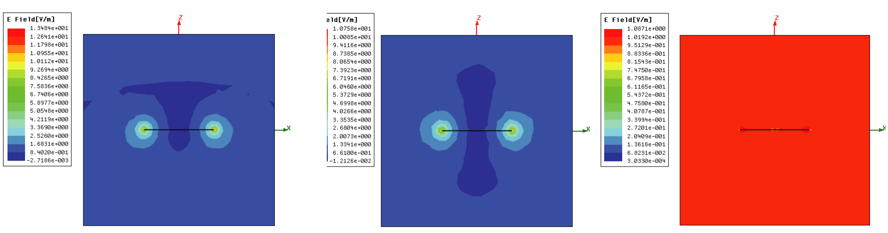
(a) k=(0,0,-1), E_i=(1,0,0) (b) k=(0,1,0), E_i=(1,0,0) (c) k=(0,1,0), E_i=(0,0,-1)

Figure 4. Total electric field distribution shown in the xz plane of the simulation on the square aluminium film.

the film, the magnitude of the electric field drops dramatically. In the case shown in Figure 4(c) it is noted that the incident wave can propagate un-attenuated across the film. The film does not affect the propagation of the incident wave. In conclusion, if the wave is expected to propagate well, the electric field of the incident uniform plane wave should be orthogonal to the conducting sheet. The conclusion made by simulation complies with the conclusion by theory presented before.

The shape of the DVD disc is quite different from the square sheet discussed ahead. Hence, further simulation is done by replacing the square metal sheet in Figure 3(a) by the real disc aluminium layer shown in Figure 3(b). This disc layer is also illuminated by the three forms of incident plane wave applied on the square sheet before. After the simulation processing, the magnitude of r.m.s phasor of total electric field distribution in the xz plane at 923 MHz are shown in Figure 5.

For the third case shown in Figure 5(c), in which the electric fields are orthogonal to the disc, the simulation result is very close to that of the simulation on square sheet which indicates that no matter the shape of the very thin metal film is, it does not affect the propagation of the incident wave in this situation. However, for the first and second types of incident waves, in which the electric fields are tangential to the disc, the simulation results are different from those of the simulations on a square sheet. There occurs some resonance between the incident wave and the disc film. The resonance is actually caused by the size of the disc. As shown in Figure 1(a), the diameter of the metal layer in the disc is about 120 mm which is very close to the half wavelength at 923 MHz. The resemblance makes the aluminium layer in the disc work as a very fat half wavelength dipole under the incidence of properly polarized waves. Because the aluminium layer is in its transverse directions very fat, we expect that the Q factor



(a) k=(0,0,-1), E_i=(1,0,0) (b) k=(0,1,0), E_i=(1,0,0) (c) k=(0,1,0), E_i=(0,0,-1)

Figure 5. Total electric field distribution shown in the xz plane of the simulation on the aluminium film in the disc.

of this resonance is very low. It is also verified by the simulation software HFSS that the maximum electric fields on the edge of the disc excited by the incident wave are held somewhat constant along a wide frequency band (400 MHz centered at 923 MHz). Therefore, this resonance can be ignored in these two cases of incident waves in which the electric field is tangential to the disc.

3.3. Simulation on Multiple Discs

The simulation on multiple discs is carried out by another simulation tool CST in this subsection. The number of the discs is extended to be 180 in the simulation. A model was built firstly which is shown in Figure 6.

The simulation model is still illuminated by three types of uniform

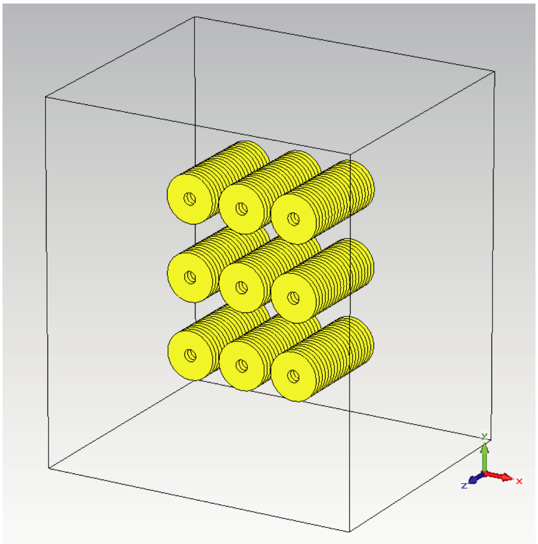
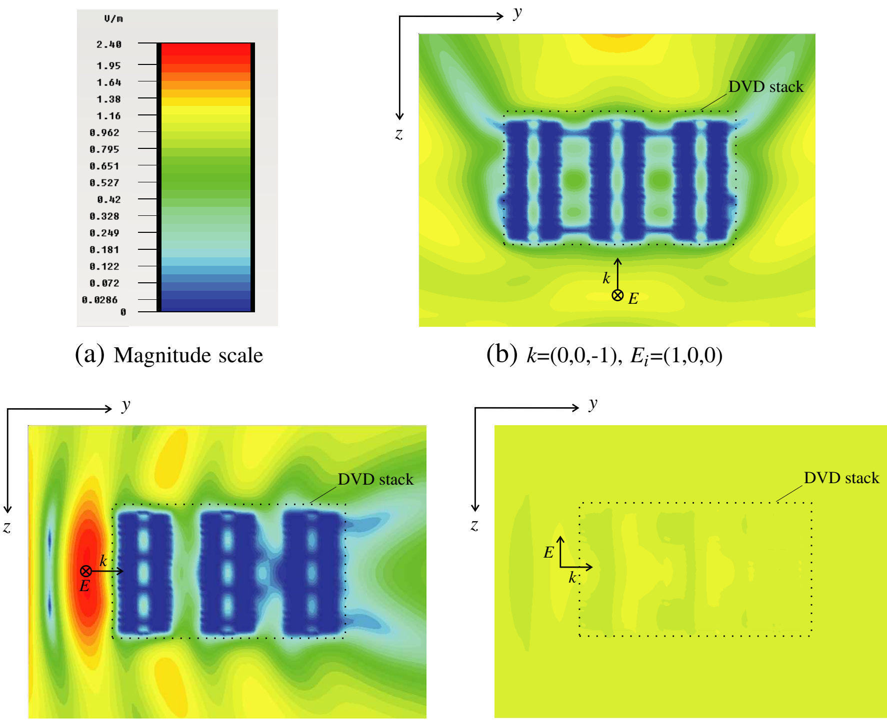


Figure 6. Simulation model of multiple discs. Along the x axis, there are 3 discs in parallel, the distance between the centres of the adjacent discs along x axis is equal to the DVD case width 136 mm. Along the y axis, there are also 3 discs in parallel, the distance between the centres of the adjacent discs along y axis is equal to the DVD case length 190 mm. Along the z axis, there are 20 discs in parallel, the distance between the centres of the adjacent discs along z axis is equal to the DVD case thickness 14 mm. Hence, in total there are $3{\times}3 \times 20 = 180$ discs. The DVD case and other materials included in each disc except the metal sheet are eligible in the model for the purpose of simplicity.

plane wave as which were used and introduced in Subsection 3.2. The simulation results are shown in Figure 7.

As shown in Figure 7(b) and Figure 7(c), in which the electric field of the uniform wave is tangential to the discs, the wave is very hard to penetrate the DVD stack. However, for the uniform plane wave which electric field is normal to the discs as shown in Figure 7(d), the wave can go through the stack without significant losses.

Therefore, the conclusion can be drawn again that the wave which electric field is normal to the disc can propagate well within the stack consisting a large number of DVDs.



(a) Magnitude scale

(b) k=(0,0,-1), E_i=(1,0,0)

(c) k=(0,1,0), E_i=(1,0,0)

(d) k=(0,1,0), E_i=(0,0,-1)

Figure 7. Electric field distribution when three types of uniform wave meeting a DVD stack. The electric field is shown in a plane which is parallel to the yz plane and in the middle of the stack. The dashed closed line shows where the DVD stack is. In each sub-figure the propagation and the electric field direction have been marked. The scale of the electric field magnitude is given in sub-figure(a) for understanding the other sub-figures.

4. INVESTIGATION OF TAG LABELING METHOD

In this section, the method of a tag labeling on a regular DVD film is investigated by experiment. The facilities and protocols deployed in the measurement are given. The tag used here is manufactured by AVERY DENNISON (Model AD 220). The protocol employed is EPC C1G2. The reading range of the tag in free space is about 6 m under Australian UHF RFID regulations [12]. The tag is approximately an electric dipole with an inductive loop placed near the connection to the chip. The RFID reader (Model ID ISC.LRU2000) by FEIG Electronics and 8 dBi gain linearly polarized reader antenna (Model S9028P) by Cushcraft Corporation, were employed here to detect the tag attached on a packaged DVD. In order to simplify this investigation, instead of tagging multiple packaged DVDs and piling up them into a stack, only one tag was attached on single packaged DVD and this packaged DVD is placed in a shielding tunnel surrounded by electromagnetic wave absorbing foam. The absorbing foam is manufactured by the Emerson & Cuming company for the frequency range from 600 MHz to 4 GHz. These absorbing foams can achieve a maximum of -22 dB reflectivity around 1GHz. The inside space of the tunnel can be considered to be effectively free space. Appropriate experiments were conducted to obtain various reading ranges of the tag on the DVD case by varying three factors: (i) the position of the tag on the DVD case; (ii) the orientation of the DVD case in relation to the propagating wave from the reader; and (iii) the reader antenna's polarisation. The details of the experiments are listed in the following two subsections categorized by the first variable: the position of the tag on the packaged DVD.

4.1. Tag Lying on the Case Cover

First, two situations when the tag lies on the case cover are tested. The two situations are tag lying at the bottom of the case cover and tag lying in the middle of the case cover as shown in Figure 8. The readability of the tags are given in Table 1.

Necessary interpretation for understanding Table 1 are discussed as follows. As mentioned before, there are three variables in the reading range experiments. These variables are all expressed in Table 1. The Symbols "(a)" and "(b)" denote the position where the tag is attached on the DVD case as shown in Figure 8(a) and Figure 8(b) respectively. The symbols "$\uparrow$" "$\rightarrow$" present the reader antenna's polarization; "$\uparrow$" means the vertical polarization. "$\rightarrow$" means the horizontal polarization.

In the first column of Table 1, some DVD case face names are listed. Those face names are used to distinguish the orientation of

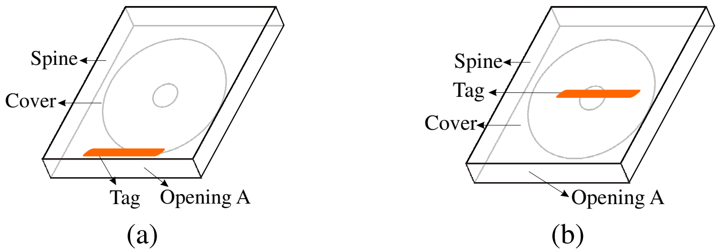


Figure 8. Tag lying on the case cover.

Table 1. Reading range test results of the tag shown in Figure 8.

	(a)↑	(a)→	(b)↑	(b)→
Opening A	VL	NR	S	NR
Spine	S	S	NR	NR

the DVD case in relation to the direction of the propagating wave from the reader. Particularly, the information in a row beginning with a face name is obtained when this face is perpendicular to the propagating wave from the reader. The situation when the propagating wave is perpendicular to the case cover is not investigated, since the propagating wave hardly penetrates through the conducting sheet of the DVD as concluded in Section 3. The DVD case always stands on a piece of polystyrene foam when it is tested. "Stands" means that no matter which case face is perpendicular to the propagating wave, the DVD case is always placed to make the longer side of the face vertical. The capital letters in the table stand for the reading range of the tag, where "VL", "L", "M", "S" and "NR" mean the reading range is very long ($> 3\,\mathrm{m}$), long ($2\,\mathrm{m}$–$3\,\mathrm{m}$), medium ($1\,\mathrm{m}$–$2\,\mathrm{m}$), short ($0.2\,\mathrm{m}$–$1\,\mathrm{m}$) and nearly not readable ($< 0.2\,\mathrm{m}$) respectively. According to the above interpretation, the cell identified by the intersection of row "Spine" and column "(a) ↑" shown content "S" can be understood as that the reading range of the tag shown in Figure 8(a) is between $0.2\,\mathrm{m}$ and $1\mathrm{m}$ when the reader antenna's polarization is vertical and the case spine is perpendicular to the propagating wave and the longer side of the spine is vertical. The interpretation above is also suitable for understanding Table 2 corresponding to the relevant figure.

By observing row "Opening A", it is found that the change in polarization affects the reading range dramatically. This is easy to understand because both the tag antenna and the reader antenna are linearly polarized, and they have to be matched well to obtain long reading range. The reading ranges in row "Spine" are all very limited, since when the case spine is perpendicular to the propagating wave, the polarization of the tag shown in Figure 8 is always orthogonal to the reader's polarization no matter the reader's polarization is vertical or horizontal. By comparing the columns with symbol "(a)" and the columns with symbol "(b)", it is found that the tag placement shown in Figure 8(a) performs much better than (or at least equally with) the tag placement shown in Figure 8(b). The degradation of the tag shown in Figure 8(b) is caused by the disc underneath, which as is concluded in Section 3 can still be regarded as a good metal sheet.

4.2. Tag Folded on the Case Face: Opening A and Spine

The tag folded on the DVD case instead of lying on the case is discussed here. There are mainly two types for the tag folded on the DVD case which are shown in Figure 9. The test results of the tag reading range are given in Table 2. By observing the results in Table 2, it can be seen that the two tag placements shown in Figure 9 are only sensitive to the horizontal polarization. This result can be understood by resolving the electric field along various sections of the tag. The part on the case opening A does couple to the horizontal component of electric field, with an effective length equal to the minimum dimension of the case. The other parts of the tag on the front and back cover faces are orthogonal to the horizontal electric field, so they do not couple to this field.

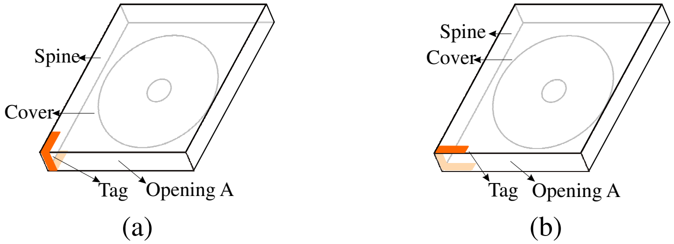


Figure 9. Tag folded on DVD case.

Table 2. Reading range test results of the tag shown in Figure 9.

	(a) ↑	(a) →	(b) ↑	(b) →
Opening A	NR	M	NR	M
Spine	NR	M	NR	M

The conclusions of this section are:

(i) Once the tag is placed above the disc top surface, its reading range will be degraded because of the disc underneath.

(ii) The whole tag shown in Figure 8(a) can couple to the incident uniform wave when the electric field of the incident wave is parallel to the tag axis which also indicates that the electric field is tangential to the disc. This tag obtained a very long reading range on a single DVD in free space as shown in Table 1. However, when a large number of packaged DVDs are piled up in a stack, the penetrability of this incident wave into the DVD stack should be considered. According to the analysis in Section 3, the 30 nm aluminium film in DVD disc is still an effective metal layer which diminishes the tangential electric field near the layer. As a result, it is predicted that this type of incident wave cannot transmit well in a DVD stack and effectively couple to the tag.

(iii) The tags shown in Figures 9 can couple to the incident uniform plane wave in which the electric field is orthogonal to the DVD. This type of incident wave is considered to be capable of penetrating deeply into the DVD stack. However, the effective length coupling to the tangential electric field of these two tag placements is only equal to the minimum dimension of the DVD case which is much less than the effective length of the tag shown in Figure 8(a).

All in all, once a large number of packaged DVDs is piled up, a tradeoff has to be made between the wave penetrability related to the polarization type and the effective length of the tag which is related to the labeling method of the tag on the DVD. Three testing schemes are selected to investigate this tradeoff as shown in Figure 10.

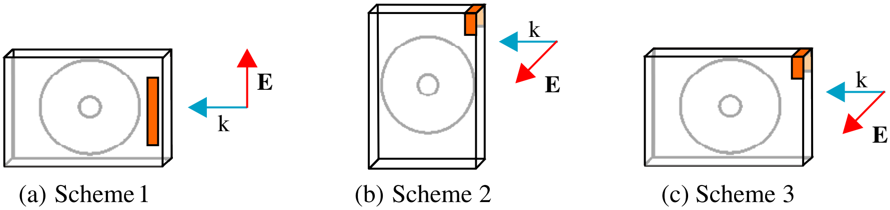


Figure 10. Three selected testing schemes. Each packaged DVD placement in a DVD stack, and the tag labeling method on it in relation to the interrogating wave are defined. In addition, the red arrow presents the electric field of the linear polarization, the blue arrow denotes the incident direction.

5. DVD DETECTION IN A STACK

5.1. DVD Stack Description and Testing Strategy

As mentioned at the beginning, the paper aims to detect 2000 DVDs in a stack by a UHF RFID system. In the following, the shape of the 2000 DVD-stack is described.

As indicated by the dimensions of a packaged DVD shown in Figure 1(a), the packaged DVD has a volume of 0.136 m by 0.190 m by 0.014 m, i.e., 0.00036176 cubic meters. 2000 packaged DVDs have a volume of 0.724 cubic meters. A cube of side 0.898 m would have that volume. The distance 0.898 m is approximately 64 times the DVD case thickness (0.014 m) and 5 times DVD case length (0.190 m) and 7 times DVD case width (0.136 m). In total, the number in such a DVD stack would be 64 by 5 by 7, i.e., 2240 DVDs. By implying the three testing schemes in Figure 10 to the 2240 DVD stack, three forms of the stack is obtained as shown in Figure 11. (Only the tagged DVDs at the bottom of the stack are shown in Figure 11.)

The instinctive perspective for reading all the 2000 DVDs within this described stack is to place the reader sufficiently far from the stack for all DVDs to fall within the main lobe of the reader antenna radiation pattern as shown in Figure 12(a). All labeled DVDs will be read if there is sufficient power density at the position of the furthest tag to do so. However the perspective above does not take into account the concept that the reading beam will be weakened by passing through the tags closest to the reader antenna. In our studies we found neither theory nor observation to support the belief that it is possible to place

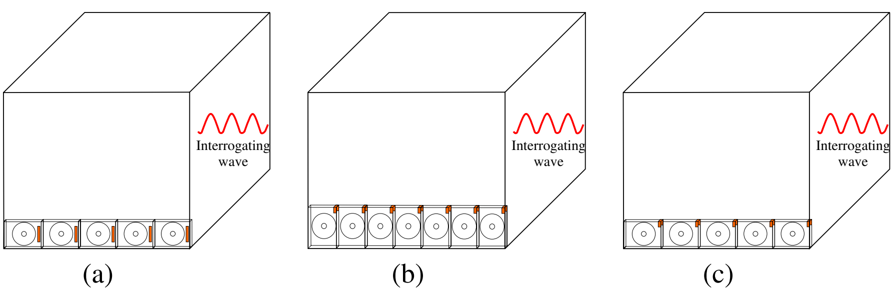


Figure 11. Three forms of DVD stack in terms of the three testing schemes. For testing schemes "1" and "3", there are DVDs 5 deep corresponding to the interrogating wave as shown in sub-figure(c) and sub-figure(c) respectively; for testing scheme "2", there are DVDs 7 deep as shown in sub-figure(b).

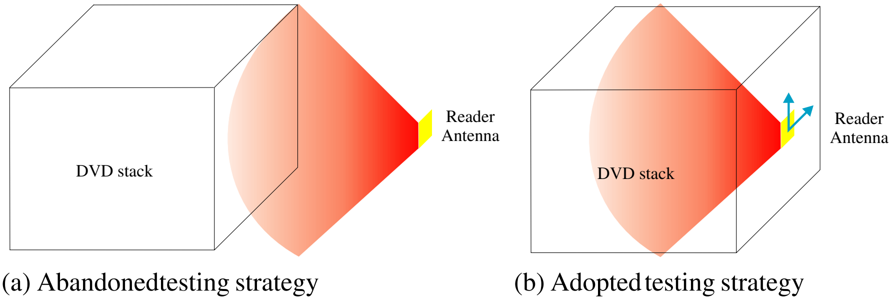


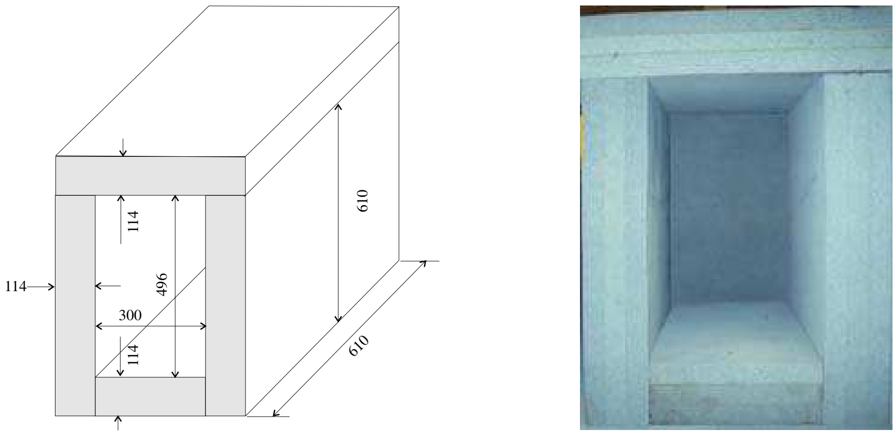
Figure 12. Testing strategy illustration.

the reader at a sufficient distance from a dense DVD stack to place all tags in its main lobe and then read all those tags. Instead, the testing strategy we adopt is to place the reader against the surface of the stack as shown in Figure 12(b). Certainly, the reader cannot read all the tags from one position. But by moving the reader antenna along three dimensions of this stack, the tags in different portions of the stack can be detected. The reader antenna is free to move along two surface dimensions as shown by the blue arrows in Figure 12(b). However, for the depth dimension, the placements of the reader antenna only gets two options either at the front of the stack or the back. Only one reader antenna is deployed in the tests of this paper, multiple reader antennas could be deployed after considering the interference among them [13].

As discussed above the depth dimension is the most significant dimension to make all the tags in the stack readable. Hence, it is not necessary to do an experiment on a 2240 packaged DVD stack. Instead, a packaged DVD stack with a much smaller surface from the view of the reader antenna but a greater depth than half the depth of the 2240 DVD stack is adequate to imitate part of the stack. If all the packaged DVDs in the small stack can be read successfully, we expect 2240 packaged DVDs can be read by moving the reader antenna.

In order to ensure there is no reflection and diffractions occur to reach the tags at the back of the stack, the small DVD stack is placed in the aperture surrounding by absorbing foam shown in Figure 13.

As introduced at the beginning of this section, all the packaged DVDs in the stack will be piled up in relation to the incident wave according to the requirements of each testing scheme shown in Figure 10. Then for the aperture shown in Figure 13, there are two types of DVD stack. First, for testing scheme "2", there are 160 DVDs 20 wide by 2 high by 4 deep filled in the aperture as shown in Figure 14(a). Secondly, for testing schemes "1" and "3", there are 180 packaged DVDs 20 wide by 3 high by 3 deep filled in the aperture as shown in Figure 14(b). The depth of the two types of the stack is deeper than half that of the 2240 DVD stack.



(a) Schematic diagram, unit: mm (b) The real aperture

Figure 13. Aperture structure illustration. The absorbing foams used here are the same to those in the shielding tunnel introduced in Section 4. After careful calculation not shown here, it is concluded that the reflection caused by the absorbing foam inside the aperture can be ignored.

(a) Stack for testing scheme "2" (b) Stack for testing schemes "1" and "3"

Figure 14. Two types of DVD stack in the aperture.

5.2. Single Tagged DVD in a DVD Stack

In this subsection, only one packaged DVD at the end of the DVD stack in the aperture is labeled. The reading range of this tag labeled on the DVD is tested using the three testing schemes selected at the end of Section 4 respectively. The shape of the DVD stack, either the one shown in Figure 14(a) or the other shown in Figure 14(b), used in the experiment depends on the requirement of each testing scheme.

The testing results are given in Table 3. The numbers in the first row of Table 3 present the three selected testing schemes. In the first column, the reader antennas used in the experiment are given. They are the circularly polarized antenna with gain 5.7 dBi (Model ISC.ANT.U250/250-FCC) manufactured by FEIG Electronics company, and the linearly polarized antenna with gain 8 dBi (Model S9028P) manufactured by Cushcraft Corporation. According to the experiments, it is found that all the three testing schemes are capable of reading the tag on the DVD at the end of the stack and there can be a distance between the reader antenna and the front side of the stack. Therefore, the reading range of the tag in the stack consists of two parts. One is inside the DVD stack, the other one is outside the DVD stack, for which propagation is in free space.

No matter which testing scheme is deployed, once the tag at the end of the stack can be read, we will conclude that it might be possible to identify all the DVDs in the stack if they were all labeled, but this conjecture will have to be tested. Hence, the reading ranges outside the stack become critical to judge this possibility, but the reading ranges inside the stack, which are all approximately equal, are not. That is the reason why only the outside reading range of the tag are given in Table 3. Please note that all the tests are under 1.26 W EIRP radiation power from the reader antenna. This radiation power is much lower than the maximum power limitation (4 W EIRP) in Australia and America. Some entries in the table are intentionally left blank, because of the obvious polarization mismatching condition between the tag antenna and the reader antenna in the relevant testing scheme.

Table 3. Outside reading range of the tag at the end of the DVD stack.

	1	2	3
8.7 dBic Circular polarization	205 mm	1210 mm	675 mm
8 dBi Linearly polarization ↑	150 mm		
8 dBi Linearly polarization →		840 mm	570 mm

By comparing the outside reading ranges obtained by the circularly polarized antenna and these by the linearly polarized antenna, it is apparent that the former has a generally better performance than the latter. Theoretically, this superior performance should not happen, since the tag placements in these schemes only couple to one kind of linear polarization as concluded in Section 4. We could not give an reasonable explanation on this issue. But based on the observation, in the following experiments, only the circularly polarized antenna is deployed.

It is also observed that the reading range obtained by adopting the testing scheme "1" in which the tag is unfolded is much less than those obtained by adopting the other testing schemes in which the tag is folded. This observation illustrates the penetrability of the incident wave plays a more significant role than the effective length of the receiving tag antenna in obtaining long reading range.

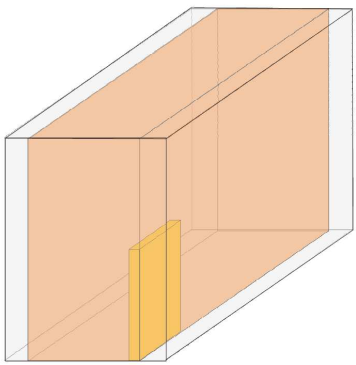
The experiment in this subsection was conducted by labeling one DVD at the back of the stack. It does not take into account the negative effects when multiple DVD are labeled: (1) the mutual coupling among the tags, (2) the weakened effect of the interrogating wave after passing through the tags in front. In the following discussion, these three testing schemes are further investigated by labeling multiple tags in the DVD stack.

5.3. Multiple Tag Detection in the DVD Stack

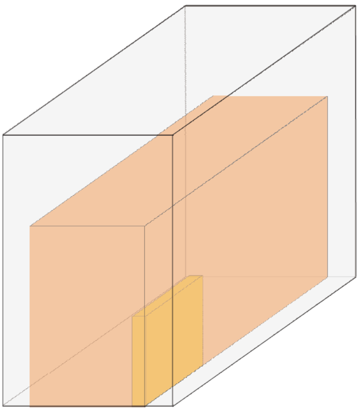
In this subsection, multiple tags will be placed on DVDs in the stack and tested under the testing schemes "1", "2" and "3". Only the circularly polarized reader antenna is used, since as observed in Subsection 5.2 this one has better performance. In addition, the radiation power is set to be the allowed maximum power (4 W EIRP) in Australia.

Because the adjacent foam may disturb reading, and the circularly polarized antenna's main lobe cannot cover the front surface of the DVD stack once the antenna is close to the stack, not all the DVDs in the stack are labeled. The area occupied by the labeled DVDs within the DVD stack is shown in Figure 15. In detail, Figure 15(a) is used to examine the testing scheme "2" in which there are 160 DVDs in total and 112 DVDs are labeled, and Figure 15(b) is used to examine the testing scheme "1" and "3" in which there are 180 DVDs in total and 84 DVDs are labeled.

The readable ratio is defined as the ratio of the number of the detected labeled DVDs to the number of the labeled DVDs in the aperture. The higher readable ratio of the testing scheme is, the more likely the testing scheme could be applied. The readable ratios



(a) Stack for testing scheme "2"



(b) Stack for testing schemes "1" and "3"

Figure 15. Labeled area and DVD placement in the tested stack. The outermost box presents the DVD stack in the aperture shown in Figure 13. The pink box presents the area occupied by the labeled DVDs. One of the labeled DVD is shown by the orange box.

of the three testing schemes are 37%, 98.2% and 97.6% respectively. According to the above testing results, the testing scheme "1" is totally abandoned and the other two testing schemes are further verified in Section 6. The imperfection of the readable ratio obtained by adopting the testing scheme "2" and "3" is caused by the miss-reading of the DVDs on the remote edge of the labeled area where the sufficient interrogating wave is hard to reach.

6. FURTHER VALIDATION

The testing schemes "2" and "3" have been verified as having a good probability of detecting a large number of DVDs, up to 2000, in Section 5. However, the validation in Section 5 is not very practical, since it did not consider the real requirement of the industry in terms of the method of packaging and stacking a large number of DVDs, and the number of tagged DVDs in the experiment in Section 5 is very limited, only about 5% of the ultimate number of tagged DVDs (2000). Hence, in order to make this validation more solid, the testing schemes are examined further in terms of four aspects: (i) taking the protocol capacity of anti-collision into account once the number of DVDs in a stack goes up to 2000 or even more; (ii) expanding the number of DVDs in a testing stack; (iii) adopting a more realistic experimental environment; (iv) considering the method used by industry in stacking a large number of packaged DVDs.

6.1. Q Parameter in EPC C1G2 Protocol for Anti-Collision

Q is a parameter that an interrogator uses to regulate the probability of tag response. An interrogator commands tags in an inventory round to load a Q-bit random (or pseudo-random) number into their slot counters. The tags in their arbitrate state decrement their slot counter every time when they receive a QueryRep command from the interrogator. The tags reply when the value in their slot counter is zero. Q is an integer from 0 to 15 [14].

In our case, the maximum number of the tag in the stack is about 2000. Within the range of available Q factors, it may be assured that the probability of collisions is low. More details of anti-collision algorithm in RFID systems could be found in [15].

6.2. Method of Packaging and Stacking DVDs in Industry

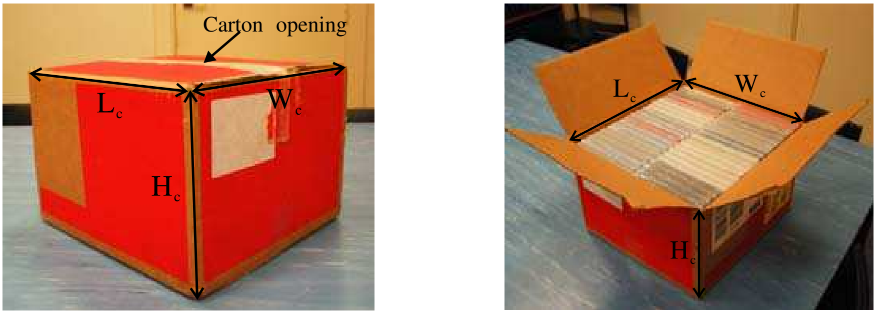
The method of packing and stacking a large number of DVDs in industry is investigated. It is found that large number of DVDs are usually distributed in cartons, and the cartons with DVDs are stacked on a pallet for storing or shipping. In this subsection, the dimension of the carton and pallet which are used widely in industry are introduced respectively.

The carton commonly used for distributing DVDs in industry is shown in Figure 16.

A pallet is a flat structure that supports goods while being lifted by jacking devices. The pallet in this paper only refers to a wooden one since most of them are wooden. A picture of a real pallet is shown in Figure 17. The dimension of the pallet is regulated in different countries and regions which can be found in [16]. In the pallet used in the following discussion is the Australia one which top surface size for sustaining goods is 1165 mm $\times$ 1165 mm.

6.3. Experiments

In this section, the testing schemes "2" and "3" are further evaluated by expanding the number of tagged DVDs and adapting the realistic testing environment of stacking cartons on a pallet. The testing processes are discussed in the following two sub-subsections. Because, historically, the testing scheme "3" was investigated before the testing scheme "2", it is reported first below.



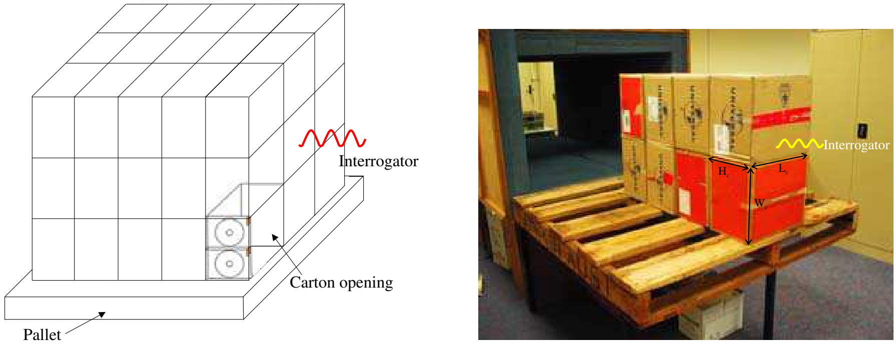
(a) Packaged carton (b) Opened carton

Figure 16. DVD carton and its dimensions. The carton is a cardboard box with length $L_c = 300\,\mathrm{mm}$, width $W_c = 280\,\mathrm{mm}$ and height $H_c = 205\,\mathrm{mm}$. The carton is just suitable to fit in 40 DVDs as shown in Figure 16(b). The spine of each DVD package is perpendicular to the bottom of the carton and the 40 DVDs are stacked into two rows, 20 for each row.

Figure 17. A sample of a real pallet.

6.3.1. Testing Scheme "3"

For the testing scheme "3", a large number of DVDs are piled up in cartons resting on their broad sides on an Australian pallet as shown in Figure 18(a). The width of each carton is placed to be vertical on the pallet. The carton opening is towards to the interrogator. To describe the DVD stack, using the interrogator as the position reference, we use the term height for a vertical dimension of the stack, depth for a front to back dimension of the stack, and width for a side to side dimension of the stack. Hence, there are three cartons along the stack height, three cartons along the stack width, five cartons along the stack depth. In total there are 45 cartons which contain 1800 DVDs. If a 3-deep DVD carton is successfully read, we will expect that all the tagged DVDs in



(a) Diagrammatic DVD stack (b) Real DVD stack

Figure 18. The DVD stack structure for testing scheme "3".

the stack could be read if we were prepared to move the interrogator along the height and width dimension in the front face of the stack, and then read from the back face by the same method of mobilizing the reader antenna as described in Section 5.1. One of the cartons at the right and bottom corner of the stack is made transparent in Figure 18(a). Two DVDs in the transparent carton are drawn to show the method of DVDs stacking in the carton and tag labeling on the DVDs. The tags are presented in the color orange.

Because of the limitation of the number of DVDs and tags, the experiment is not conducted on the stack shown in Figure 18(a). The number of the tagged DVDs used in the experiments of this section is 320 which can be distributed into 8 cartons. These cartons are piled up as a certain shape on the pallet shown in Figure 18(b) in which there are 8 cartons 1 wide by 2 high by 4 deep. As mentioned before, we intend to read all the DVDs in the front three deep cartons. To achieve this, the interrogator antenna is deployed just against the front face of the stack and 4 positions of the reader antenna's centre in relation to the front face are marked by the blue patches in Figure 19(a). The readable ratio defined before is used here again to illustrate the feasibility of the testing scheme in detecting all the DVDs in the stack. In this case the readable ratio is 77.1%. One thing should be explained is that to obtain the readable ratio in this case, the denominator is not 320 although all of the 320 DVDs have been labeled. The denominator adopted is 240 since we do not seek the detection of the 80 DVDs those are in the 4-deep cartons and are beyond our aim of reading 3-deep DVDs.

It is found that with the increase of the depth, the number of the misreading tags is increased. The misreading tags are usually found on the side edge of the stack. Those misreading behaviors are believed to

(a) 4 position test

(b) 12 position test

Figure 19. The reader antenna's positions in relation to the stack in terms of the testing scheme "3".

be caused by the limitation of the reader antenna's radiation pattern, i.e., the relatively large radiation power from the reader antenna only concentrates in a certain area in the stack, which is here named as the effective reading area. The effective area becomes narrow with the increase of the depth in the stack because of the attenuation along the depth dimension, and the power absorption and consumption of the tags in front.

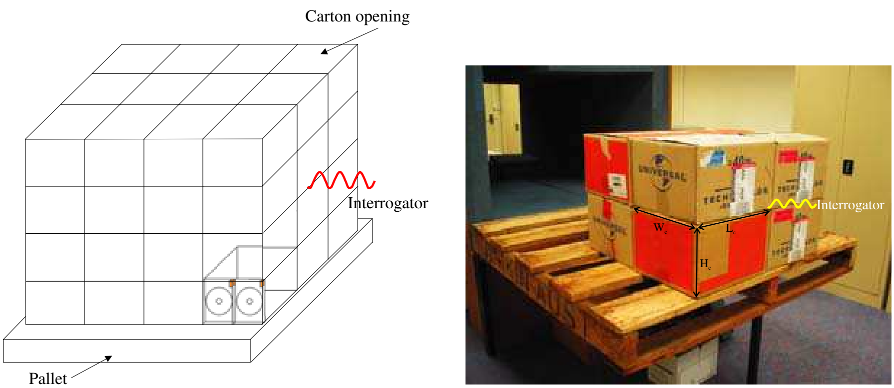
The limitation of the reader antenna's radiation pattern can be compensated by placing the reader antenna against the stack front face in more positions. For example, the experiment is re-conducted by placing the reader antenna at 12 positions in front of the stack to read the tags in different parts of the stack. The 12 positions of the reader antenna's centre in relation to the stack front face is shown by the 12 blue patches in Figure 19(b). The readable ratio of this experiment is 96.25%. Apparently, the increase of the readable ratio is only at the expense of time. It has been established by DVD position swapping that the misreading tags are caused by the tag's weak performance. If there had been no weak tags there would have been no misreads.

6.3.2. Testing Scheme "2"

For the testing scheme "2", a large number of DVDs are stacked in cartons resting on their bases on an Australian pallet as shown in Figure 20(a). The height dimension of each carton is vertical on the pallet. The face defined by the carton height and length is towards to the interrogator. The real cartons fully filled with DVDs are stacked as the shape on the pallet shown in Figure 20(b) in which there are 8 cartons (320 DVDs), 2 wide by 2 high by 2 deep.

The experiments for the testing scheme "2" were conducted similarly to those for the testing scheme "3". First, the experiment was conducted by placing the reader antenna at 4 positions in front of the stack as shown by the blue squares in Figure 21(a), and then the experiment was conducted by placing the reader antenna at 10 positions as shown in Figure 21(b). The readable ratios of the two experiments are 76.56% and 98.75% respectively. It has been established by DVD position swapping that the misreading tags are caused by the tag's weak performance.

However, as addressed before, the reader will be moved to the back side of the stack to detect the tags in the third and forth deep cartons,

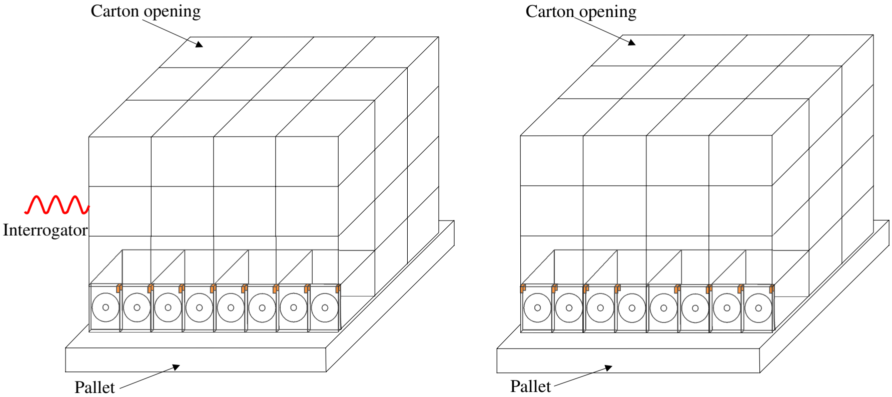


(a) Diagrammatic DVD stack (b) Real DVD stack

Figure 20. The DVD stack structure for testing scheme "2".

(a) 4 position test (b) 10 position test

Figure 21. The reader antenna's positions in relation to the stack in terms of the testing scheme "2".



(a) Un-symmetrical DVD stack (b) SymmetricalDVD stack

Figure 22. The un-symmetrical and symmetrical DVD stack.

as shown in Figure 22(a). Because of the un-symmetrical structure of the tag labeling on DVDs, once the reader is moved to the back side of the stack, the distance between the tags and the reader ranges from $0.5\times W_c$ to $2\times W_c$ (W_c is the width of the DVD carton). This is different from the situation when the reader intends to detect the tags from the position against the front side of the stack, i.e., the distance between the tags and the reader ranges from $0\times W_c$ to $1.5\times W_c$. This longer distance could decrease the readable ratio.

The method to solve this problem is to stack the whole tagged DVDs symmetrically about the center plane of the stack depth, as shown in Figure 22(b). Then the two deep cartons and the tags in these cartons in the front part of the stack and those at the back part of the stack are symmetrical about the center plane of the stack depth.

7. CONCLUSION AND FUTURE WORK

By careful considerations of the electromagnetic properties of the DVD's components, and the way of packaging, distributing and stacking DVDs in industry, two configurations with which it is possible to detect a large number of DVDs densely stacked are proposed. The number is in the range of 2000. Each package includes the testing scheme (the tag labeling method corresponding to the interrogating wave), the testing strategy (the reader antenna placement and movement) and the stacking policy of DVDs on a pallet in industry. The readable ratio of the two solutions are 96.25%

and 98.75% respectively by randomly using the commercial tags in existence. The imperfection reading is caused by the weak performance of the undetected tags. If the weak tags were eliminated, the readable ratio of both solution would be 100%. Besides the realization of detecting 2000 DVDs in item-level tagging, this paper also provides a process and method for achieving item-level tagging of other products in which the number of the products goes up to thousands. As seen in this paper, by using the commercial tags and without eliminating the weak tags, 100% readable ratio cannot be achieved. Our suggestion is to solve this unperfect reading problem completely, i.e., to get the 100% readable ratio, a new type of tag antenna which is optimised for folding across the spine of the DVD case should be designed and that design could be done in the future.

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