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UHF RFID TAGS WITH PRINTED ANTENNAS ON RECYCLED PAPERS AND CARDBOARDS

UHF RFID-ZNAČKE Z NATISNJENIMI ANTENAMI NA RECIKLIRANEM PAPIRJU IN KARTONU

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The integration of passive RFID tags in different applications is important in order to increase product functionality. The present research was focused on the optimization of the printing process conditions for the screen printing of passive UHF RFID antennas for the box tracking in logistics and for newspaper tracking in the retail trade. The antennas were printed on uncoated and coated recycled papers and coated cardboards. Two different conductive inks were applied with a semi-automatic screen printer. Drying conditions were varied in order to obtain a good print quality and the appropriate electrical properties of the conductive printed layer on all the printing substrates. The integration of flip chips was applied to the printed antennas. At the end of our research, an analysis of the printed antennas and the final UHF RFID tags was carried out. The quality of the printed antennas was first evaluated by image analysis, after which the electrical properties, such as the impedance and radiation patterns, were measured. To analyse the quality of UHF RFID tags, the maximum reading length was also determined.
We demonstrated that working UHF RFID tags with screen printed antennas can be realized on substrates with lower quality, such as uncoated recycled papers. The main influence on the final working tag is the quality of the conductive ink itself.

Keywords: printed RFID antenna, tag integration, recycled paper, cardboard

Vključitev pasivnih RFID-značk v različne aplikacije je pomembna, da dosežemo dobro funkcionalnost izdelka. Predstavljena raziskava je bila osredinjena na optimizacijo razmer sitotiskarskega procesa, s katerim so bile natisnjene UHF RFID-antene za sledenje embalaže in časopisov v trgovinskih verigah. Antene so bile natisnjene na nepremazane in premazane reciklirane papirje in na premazane embalažne kartone. Uporabljeni sta bili dve prevodni tiskarski barvi, ki sta bili na tiskovni material naneseni s polavtomatskim sitotiskarskim strojem. Razmere pri sušenju so bile optimizirane, tako da so bile dosežene dobra kakovost in primerne električne lastnosti odtisov na vseh tiskovnih materialih. Na tiskanih antenah je bilo izvedeno kontaktiranje čipov. Na koncu raziskav je bila izvedena analiza natisnjenih anten in končno izdelanih značk. Kakovost tiskanih anten je bila ovrednotena s slikovno analizo ter z merjenjem impedance in sevalnega diagrama anten. Za določanje kakovosti končne značke je bila določena še maksimalna razdalja odčitavanja.
Dokazali smo, da je UHF RFID-značke mogoče tiskati s sitotiskom tudi na nizkocenovne tiskovne materiale, kot je nepremazan recikliran papir. Glavni vpliv na delovanje končne značke ima kakovost prevodne tiskarske barve.

Ključne besede: tiskane RFID-antene, izdelava RFID-značke, recikliran papir, embalažni karton

1 INTRODUCTION

The future of automatic identification and data capturing in the field of packaging is increasingly dedicated to radio-frequency identification (RFID), which enables wireless identification and saves a lot of time (and money) in comparison to barcode technology. RFID is an automated identification technology that consists of a reader, a reader antenna and a tag (which consists of an antenna and a chip). It uses radio waves to transfer the information between the reader and the tag at long distances. The RFID tag can work at different frequencies: low (LF: 125 kHz or 134 kHz), high (HF: 13.56 MHz) or ultrahigh (UHF: 860–960 MHz) radio-frequency ranges. Due to the fact that the higher the frequency, the larger the distance at which the information can be read, in packaging identification UHF RFID tags are mostly used.

The RFID tag can be produced conventionally by an etching process or can be printed. While the conventional production of RFID tags is still very expensive and environmentally unfriendly, many researchers are trying to produce printed RFID tags, where the electronic components are printed in-line, roll-to-roll, in the same process as the packaging layout itself. The printing, unlike conventional etching, is an additive process, and is far more ecological and economical than the subtractive etching process. This could reduce the amount of material used for production, i.e. the waste that is a side product of production, and consequently the total cost per tag. RFID antennas can be printed with different printing technologies:[1] offset lithography, flexography, gravure, ink jet, electrophotography and screen printing. Different printing technologies enable different accuracy, resolution and ink thickness. Most research has been carried out using inkjet[2–5] and screen[6–9] printing technologies. There have also been some using gravure printing,[10,11] but less with offset and flexography. Many research programmes have also been undertaken to test the performance of RFID printed antennas[12–19] and chip bonding.[20,21] Printed antennas are usually applied to different foils[22,23] or photo papers. There are also some researches made on the field of printed paper-based RFID or sensors,[17,24–29] but none of them analysed the printing RFID antennas on recycled paper and cardboard. The research in that field analysed the printing substrates from the electrical point of view and not from the graphical point of view. For this reason, in this paper the application of silver conductive ink to recycled papers and packaging cardboards is presented.

The goal of our research was to optimize the printing process and drying conditions for the screen printing of passive UHF antennas directly on packaging and paper substrates. The antennas were printed with silver conductive printing inks using a semi-automatic screen printer. After that the silicon chip was applied to the antenna. At the end of our research, the analysis of the printed antennas and final UHF RFID tags was carried out. The quality of the printed antennas was evaluated by image analysis and the resistance to abrasion, which is important if the antennas printed on packaging or on newspaper are not additionally protected with another protective layer. At the end the impedance and radiation patterns were measured. To analyse the quality of the UHF RFID, the tag reading length was determined by measuring the received power in watts.

2 EXPERIMENTS

The current investigation involved the selection of the UHF RFID antenna for the central frequency of 868 MHz (**Figure 1**), antenna printing, drying optimization, analysis of antenna printability, mounting the chip onto antenna and an analysis of RFID tag reading.

2.1 Printing

The UHF RFID antennas were printed with two conductive printing inks: SunChemical[30] (CRSN2442, SunTronic Silver 280, Thermal Drying Silver Conductive Ink) and DuPont[31] (DuPont 5064H silver conductor). As printing substrates, two coated cardboards and two recycled papers (one coated and one uncoated) were used. A RokuPrint semi-automatic screen printer and monofilament polyester plain weave mesh with 120 L/cm were used (theoretical ink volume 16.3 cm^3/m^2).

Figure 1: Antenna printing form
Slika 1: Tiskana oblika antene

The properties of the printing inks and printing substrates are presented in **Tables 1** and **2**.

Table 1: Printing inks properties[30,31]
Tabela 1: Lastnosti tiskarskih barv[30,31]

Property		SunChemical	DuPont
Solids		69–71	63–66
Viscosity		2–3	10–20
Sheet resistance: $R_\square$/mΩ for 25 µm)		10–32	≤6 on 125 µm PET film
Drying conditions	Static box oven	150 °C/ 30 min	130 °C/ (10–20 min)
	Reel-to-reel	100–130 °C/ (30–90 s)	140 °C/ (2 min)

2.2 Print penetration

The print penetration was determined in accordance with the IGT–W24 and ICP–T17 methods. At the moment of printing a quantity of ink or varnish is absorbed by the surface of the paper. This amount is determined by the absorption of the liquid in the surface recesses (roughness) and the absorption into the paper pores at the surface. With the IGT test method the sum of the two phenomena is determined: the oil absorption or varnishability. The reciprocal value of this is called print penetration. A large stain indicates a low roughness/absorption of the paper.

The final values for the print penetration were calculated according to Equation 1, where *PP* is the print penetration and *l* is stain length of the print in mm:

$$PP = 10^3/l \tag{1}$$

2.3 Optimization of drying conditions

After printing, the optimization of the drying conditions was determined to achieve the lowest sheet resistance of the prints. Based on experiments, a two-stage drying process was determined as optimal (**Figure 2**). The samples were dried according to the printing substrate and the printing ink. The optimal drying was

Table 2: Properties of printing substrates
Tabela 2: Lastnosti podlag za tiskanje

Standard	Type	Grammage (g/m^2)	Thickness (µm)	Roughness (µm) (Stylus TR200)	Porosity (mL/min) (Bendtsen)	Water absorptiveness (g/m^2) ($Cobb_{60}$)
		ISO 536	ISO 534	ISO 4287	ISO 5636-3	ISO 535
paper 1	coated recycled paper	60	60	2.226	16.00	not determinable
paper 2	uncoated recycled paper	60	113	5.706	381.00	not determinable
cardboard 1	coated cardboard	245	400	0.463	27.33	5.609
cardboard 2	coated cardboard	350	525	0.482	12.00	4.427

Figure 2: Schematic representation of two-stage (combined) drying process
Slika 2: Shematski prikaz dvostopenjskega sušenja

determined as the point where the sheet resistance of the printed samples became constant and did not get any lower with longer drying times or higher temperatures.

2.4 Analysis of printed conductive ink layer

After printing and the two-stage drying process, the analysis of the printed conductive ink layer was carried out. The print mottle, abrasion and sheet resistance of the printed ink layer were determined.

2.4.1 Print mottle

The print uniformity (print mottle) was determined using image analysis (ImageJ software). The print mottle was determined with a traditional STFI method, by calculation of the coefficient of variation (CV), where σ is the standard deviation of the grey values and R is the mean grey value:[32]

$$CV/\% = \sigma/R \times 100 \quad (2)$$

2.4.2 Abrasion

The abrasion was determined on the samples (5.1 cm × 23 cm) using a Param RT-01 Rub tester instrument (according to the standard ASTM D 5264). The printed samples were positioned on the table, and the unprinted specimen of the same printing substrate was mounted on the weight, which rubs the printed sample. The test duration is determined by the number of strokes (a stroke is one back-and-forth cycle) the sample is rubbed. The speed of the rub was 106 cycles per minute using a mass 0.9 kg. The abrasion was determined on the receptor surface of 4.8 cm × 10 cm size using image analysis after 100 (paper) or 500 (cardboard) strokes. The uncoated (and coated) recycled paper has a rougher surface than the coated cardboard and consequently the abrasion of the printing ink on the paper was much higher than on the cardboard. If 500 strokes were applied to paper, the abrasion would not be determinable using image analysis. On the other hand, after 100 strokes on cardboard there is no evident abrasion. That is why only 100 strokes were applied to paper and 500 to cardboards. The results present the proportion of the area coated with the rubbed ink on the receptor surface.

2.4.3 Resistance

The resistance was measured on the test element presented in **Figure 3** between points 1 and 2 using a DT-890G multimeter. The nominal length was L = 22 mm and width W = 3 mm. The nominal number of squares was $N_{sq} = L/W = 10.3$. The final results are given as the value of the conductive printed layer sheet resistance $R_{\square}$ (mΩ).

2.5 RFID tag analysis

2.5.1 Antenna evaluation

The numerical simulation of the antenna impedance was carried out using a commercial 3-D solver (Ansoft HFSS). In addition, the radiation patterns in the E (electric field) and H (magnetic field) planes for the paper and cardboard printed antennas were measured at an outdoor antenna-measuring polygon.

2.5.2 RFID tag reading

After the antennas had been printed and analysed, the strap chip (NXP) with impedance Z = 22 – j195 Ω [33] was assembled onto the printed antennas. Then the analysis of the RFID tag was performed using an IDS-R902 reader (IDS Microchip, Ljubljana, Slovenia). The IDS-R902 reader consists of an IDS reader and a Patch A0025 antenna (Poynting GmbH, Dortmund, Germany). The reader is based on the IDS-R902 circuit, supports the ISO18000-6 C or EPC Gen 2 Protocol and measures the strength of the modulated signal backscattered from the tag. The reader antenna (gain 4.5 = 6.5 dBi) emits circularly polarized UHF radiation with a frequency f = 867 MHz. Its output power is 400 mW (+26 dBm). The reader uses an amplitude shift keying and has a maximum input sensitivity of 25 pW (–76 dBm). The quality of the final UHF RFID tag was evaluated by measuring the power in W (dBm) for every 5 cm by moving the tag straight from the reader.

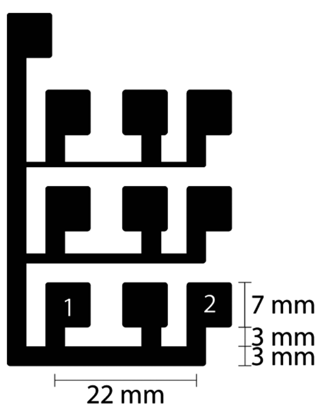

Figure 3: Test element for resistance measurement
Slika 3: Preizkusni element za merjenje upornosti

3 RESULTS AND DISCUSSION

3.1 Print penetration

Print penetration is a measure of the penetration velocity of the printing ink into the printing substrate. It represents the properties (roughness, porosity and absorptiveness) of the printing substrate. **Figure 4** shows that recycled papers have a higher print penetration than cardboards. Again, the higher penetration can be detected with uncoated recycled paper, which can be directly connected to the roughness and print mottle.

3.2 Drying optimization

The drying optimization was determined as the point where the resistance became constant with a higher temperature or longer drying. The optimal drying conditions were determined as presented in **Table 3**. Samples were first dried in the hot zone and then they were exposed to the Heat&Press process (**Figure 2**).

During the drying process, the printing substrate exposed to high temperatures changes its surface colour, which is significant when the final product is graphically designed, such as with packaging, where the colours and final product's appearance are very important. The colour difference (ΔE) of the printing substrate was determined for both printing inks (**Figure 5**). It is clear that the printing substrates printed with DuPont printing ink change their colour more than the samples printed with SunChemical printing ink, due to the higher heating temperature. Even so, all the values are very low and the colour change is hard to detect with the eye. The printing with SunChemical printing ink is also more appropriate from an ecological point of view, because of the lower drying temperature.

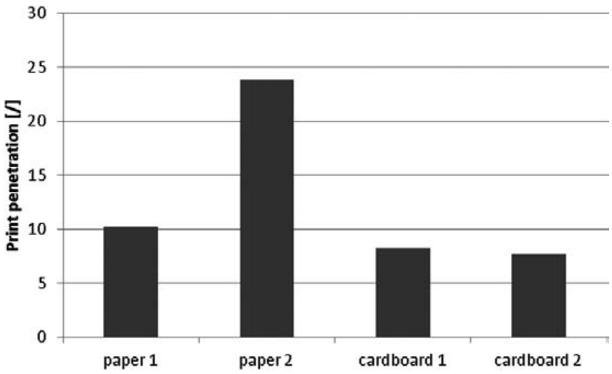

Figure 4: Print penetration of the printing substrates
Slika 4: Tiskarska penetracija na podlagah za tiskanje

3.3 Analysis of printed conductive ink layer

3.3.1 Print mottle

In **Figure 6** the print mottle for all the printing substrates is presented. The print mottle is dependent on the surface properties of the printing substrate. Usually, it is the result of an uneven ink layer or non-uniform ink absorption across the printing substrate.[34] The higher roughness (**Table 2**), print penetration (**Figure 4**) and water absorptiveness (**Table 2**) of the two recycled papers affect the higher print mottle, as presented in **Figure 6**. The difference between the two conductive inks is also obvious, with the DuPont printing ink having a slightly higher non-uniformity. The final antenna performance is also dependent on the print quality of the printed conductive lines. If the antenna is printed onto rough substrates the conductive Ag particle in ink could not be connected and the final conductivity could be questionable. In that case the final antenna performance would not be as good as expected based on the antenna design and simulation.

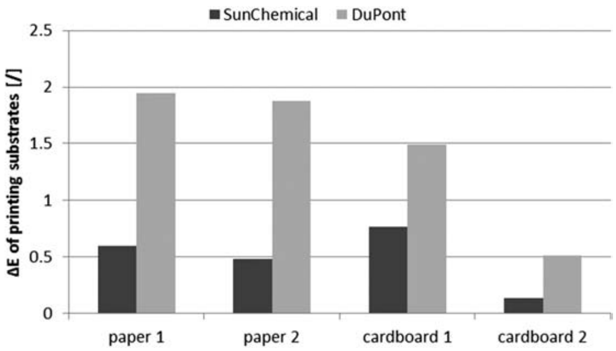

Figure 5: ΔE of printing substrates after two stages drying process
Slika 5: ΔE podlag za tiskanje po dvostopenjskem sušenju

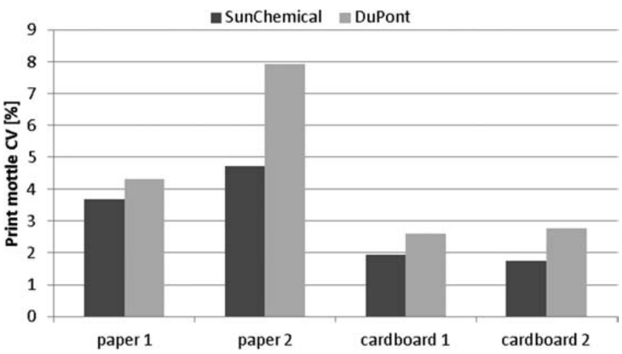

Figure 6: Print mottle
Slika 6: Tiskovna neenakomernost

Table 3: Drying conditions
Tabela 3: Razmere pri sušenju

	Hot zone				Heat&Press	
Printing substrate	Time (s)	Temperature (°C)		Printing ink	Time (s)	Temperature (°C)
Cardboard	135	115		SunChemical	10	150
Paper	90	115		DuPont	10	190

3.3.2 Abrasion

The abrasion of the printed antennas is important, while prints have to have good conductivity, which is degraded if the prints' abrasion is too high. In that case it is possible to get a inhomogeneous printed conductive layer and small holes can appear on the surface of the antenna, because of the printing substrate roughness.

In **Figure 7** it is clear that the prints printed on papers have much higher abrasion (at lower rub) than those printed on cardboard. It is also evident that the DuPont printing ink has higher abrasion than the SunChemical ink. On paper (especially on uncoated recycled paper), the binder penetrates more quickly and deeply into the substrate than on coated cardboard, and consequently the conductive silver particles remain unbounded at the surface. Moreover, the surface of the paper is rougher (**Table 2**) and when rubbed more the particles remain on the receptor (unprinted specimen), and the abrasion is higher.

3.3.3 Sheet resistance

The sheet resistance was calculated and is presented in **Figure 8**. All the samples achieved a good sheet resistance, i.e., lower than $R_{\square}$ = 100 mΩ, with the antennas printed with DuPont printing ink being even lower than those printed with SunChemical ink. In the inks' specification (**Table 1**), the specified resistances are much lower than those presented in **Figure 8**. This is because the resistances in **Table 1** correspond to a thick dry film 25 µm, while the measured thicknesses of the dry film in our experiment were much lower (the thickness was determined on a cross-section of the printed samples), between 6 µm and 10 µm, and consequently the sheet resistance is higher.

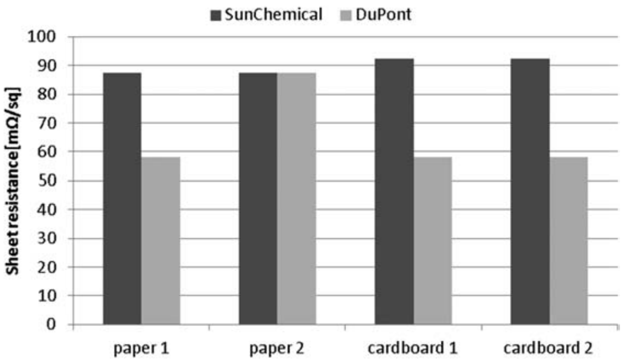

Figure 8: Sheet resistance of the prints
Slika 8: Plastna upornost odtisov

3.4 RFID tag analysis

3.4.1 Antenna evaluation

The radiation patterns in the E- and H-planes were evaluated by measurements of antennas on two printing substrates. The uncoated recycled paper (paper 2) and coated cardboard (cardboard 1) were selected as they had the highest and the lowest print mottles (**Figure 6**) and abrasions (**Figure 7**) of the four samples. The samples printed with the SunChemical printing ink were selected on the basis of lower heating temperatures, lower abrasion and smaller print mottle in comparison with the DuPont printing ink. The results revealed that the patterns are nearly the same for both measured antennas, regardless of which printing substrate was used (**Figure 9**).

The measured radiation patterns have slight irregularities in the measurement, especially at the nulls. This is

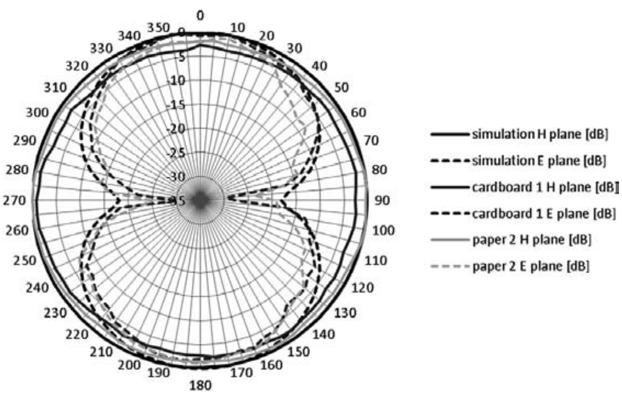

Figure 9: Radiation pattern for antennas printed on both cardboard and on recycled paper and its simulation
Slika 9: Sevalni diagram antene, natisnjene na embalažnem kartonu in recikliranem papirju ter njena simulacija

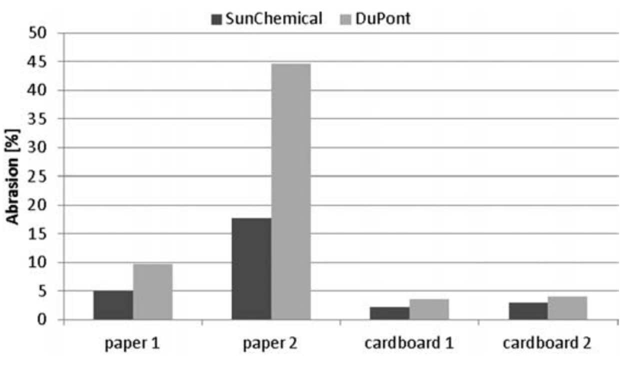

Figure 7: Abrasion
Slika 7: Abrazija

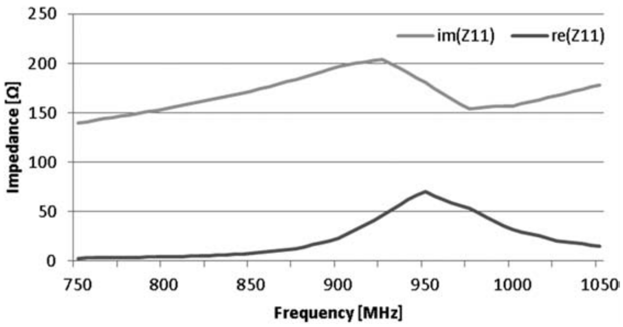

Figure 10: Simulated antenna impedance
Slika 10: Simulirana impedanca antene

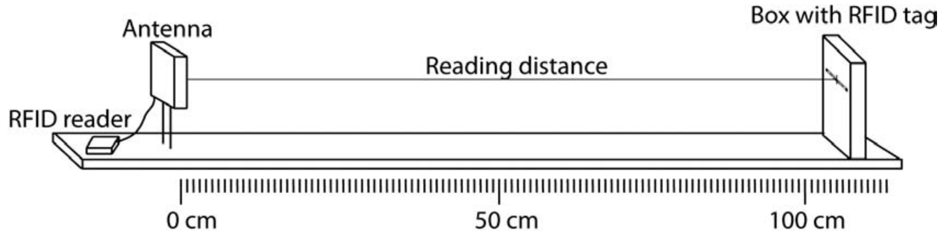

Figure 11: Measurements of tag readability
Slika 11: Merjenje berljivosti natisnjenih značk

due to the disturbance to the antenna and the obstruction of the attached balun that was used for the balanced antenna to the coaxial cable interface. Without the balun interference, the radiation patterns should be approximately the same as the simulated ones shown in **Figure 9**.

Besides the radiation pattern, the impedance of the antenna was simulated (**Figure 10**). The simulated antenna impedance of about 15 + j180 Ω at 868 MHz ensures a good match to the RFID chip impedance (22 - j195 Ω).

3.4.2 RFID tag reading

The NXP chips on strap were attached to the printed antennas and the largest reading distances with the corresponding power values were measured in a real environment on five samples, as presented in **Figure 11**. The printed antenna was oriented horizontally to the transmitting antenna. **Figure 12** shows that the power (an average of 5 measurements) diminishes with the distance of reading from around 10 nW to almost 100 pW (-50 dBm to almost -70 dBm) at one metre distance. The largest measured distance where the tags still worked was 105 cm. It was observed that the power of the tags printed on paper was a little lower than that of the tags printed on cardboard.

4 CONCLUSIONS

The analysed influences of drying conditions on the quality of the printed conductive layers were proven to be significant, not only in terms of the quality of the printing but also on the relevant electrical parameters measured on the printed antennas. A higher drying temperature increases the final conductivity. The paper and cardboard enable drying to 150 °C or a maximum of 200 °C. A higher drying temperature causes the substrate to become yellow.

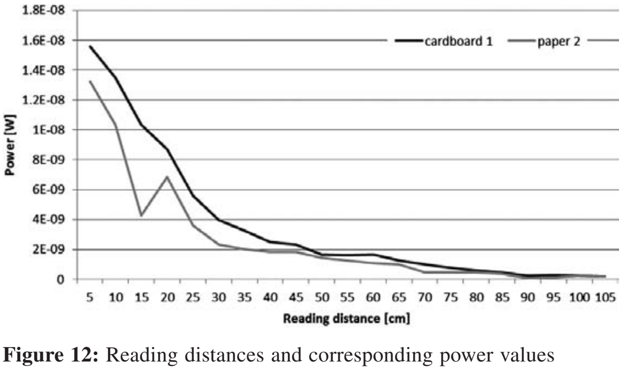

Figure 12: Reading distances and corresponding power values
Slika 12: Razdalje odčitavanja in pripadajoče vrednosti moči

The two-stage drying process with Heat&Press makes it possible to use a lower drying temperature and a shorter drying time. Comparing the printing inks, the DuPont ink has a slightly lower resistance, which is its only advantage over the SunChemical ink. On the other hand, the weakness of the DuPont ink is that it requires a higher drying temperature. SunChemical ink shows lower print mottle and has lower abrasion. It means that antennas printed with SunChemical ink are more uniform on their surface and more mechanically stable.

The printing substrate, especially the coating, has significant influences on better ink formation, higher uniformity and also on better abrasion resistance. This effect is visible especially on coated recycled paper and cardboards compared with uncoated recycled paper.

The design of the UHF antenna is appropriate for both printing substrates – no differences in radiation pattern were observed between antennas printed on coated cardboard and those on uncoated recycled paper.

By the end of our research we had shown that working UHF RFID tags with screen-printed antennas can be realized on substrates of extremely low quality, such as uncoated recycled papers. The main influence on the final working tag is the quality of the conductive ink itself.

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