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Research Article

Analysis of Silver Ink Bow-Tie RFID Tag Antennas Printed on Paper Substrates

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In this study, polymeric silver inks, paper substrates, and screen printing were used to produce prototype Bow-Tie tags. Because of increasing interest in applying passive UHF-RFID systems in paper industry, the Bow-Tie antenna used in this study was designed to work through paper. The maximum reliable read ranges of the tags were measured through stacked paper and also in air. The analysis and functioning of the antenna design are also discussed. All inks and paper substrates were suitable as antenna material and the prototype tag antennas had good reading performance. The maximum reliable read ranges were quite the same as for copper and aluminum tags studied elsewhere. This means that printed UHF tags are competitive solutions for the identification of simple mass products.

1. INTRODUCTION

The popularity of radio frequency identification (RFID) has increased considerably lately. RFID technology is used, for example, in logistics and access control. The communication and coupling in RFID systems are based on electromagnetic fields and waves and it has many advantages compared to other identification systems. For example, many items can be identified at once and no visual contact is needed. Low-frequency (LF) and high-frequency (HF) frequencies such as 125 kHz and 13.56 MHz are already used in many RFID applications, and systems which work at UHF frequencies are under research and development and their use is emerging [1].

Passive RFID tags do not have any internal source of energy, such as a battery, to support the functioning. Passive tags get all the energy needed for functioning from the electromagnetic radiation emitted by the reader. Communication between the reader and the tag is based on backscattering: reader sends energy to activate the tag and then commands to the tag which then responds by backscattering its identification data back to the reader. The basic components and operating principles of the passive RFID system are presented in [2].

Long-range systems have reading distance more than one meter. Long-range systems are coupled and the data is transmitted using electromagnetic waves and backscattering of modulated electromagnetic wave. Tags at lower frequencies work on shorter distances from a few centimetres to approximately half a meter. That kind of systems are close-coupling systems and they are coupled using magnetic and electric fields. However, longer reading distances are needed in many applications [1, 2].

Passive UHF spectrum RFID systems achieve read ranges longer than 1 minute, and thereby they are defined as long-range systems. These systems operate at the UHF center frequencies of 866 MHz (Europe), 915 MHz (Americas), and 950 MHz (Asia and Australia), and the microwave frequencies of 2.5 GHz and also 5.8 GHz. Therefore, the whole bandwidth used in UHF RFID is from 865 MHz to 960 MHz. The UHF and microwave frequencies have relatively short wavelengths, which allow construction of antennas with smaller dimensions and greater efficiency that would be possible using frequency ranges below 30 MHz [1].

Bow-tie antennas are passive dipole-type and relatively broadband microstrip UHF antennas [3]. They are suitable to be used as tag antennas for various applications. The effects of antenna and substrate materials on the performance of bow-tie tag antennas have been studied earlier in [4]. To allow comparison of these results, the tag antenna design studied in [4] is also used in the measurements carried out for this paper.

At the moment, the price of an individual tag is still too high for item-level tracking. More research must be done to create cost effective manufacturing processes, to find cheaper materials and to add integration. Printing on paper may offer one solution for this problem because it is fast, cheap, easy, and environmentally friendly tag manufacturing technique. The tags can also be printed directly on items or packages which are to be identified. Many packaging is made of paper which is cheap and environmentally friendly material. However, this paper does not tolerate etching process. Printing can be used to make RFID antennas also in circumstances where etching can not be used. Printing is an interesting technique especially for UHF tag antenna manufacturing, because at UHF frequencies, antenna pattern does not have to be thick. This is because of the skin effect. Thinner antenna means savings in material costs [5, 6].

Printing is an additive process, which means that the pattern is selectively grown to the areas wanted. There are different printing techniques which can be used to print antennas with conductive ink. Conductive inks usually consist of polymer matrix and conductive fillers. The use of conductive silver inks in tag antenna manufacturing has been studied earlier, for example, in [7]. These studies show that conducting inks are suitable for tag antenna manufacturing. Compared to pure metals, such as copper or aluminum, conductive inks cause small degradation to the antenna gain and they also affect the input impedance of the tag antenna. However, these variations and their effect on practical read ranges of the tag antennas are relatively small [7].

Different printing technologies require different ink characteristics. Some characteristics of the most typical printing processes are shown in Table 1 [5, 8].

Screen printing, gravure printing, flexography, and digital printing are typical printing processes. There are advantages and disadvantages considering each of these techniques. Screen printing is commonly used in electronic manufacturing. The ink is pressed through a stencil to the substrate with a squeegee. The advantage of this technique is that it allows printing very thin and also very thick films. One possible restrain for screen printing is the resolution. Maximum resolution is about 50 lines per centimeter [9–11].

Flexographyis a letterpress process. The figure is raised on a printing plate which is attached on plating cylinder. From the printing plate, the figure is transferred to a substrate using impression cylinder to press the substrate toward the printing plate. The thickness of printed image depends on the print speed and pressure. Flexography process allows printing on very wide variety of substrates but the resolution of figures is limited [8, 12].

Gravure printing is a technique which uses an engraved cylinder to transfer the figure to the substrate. The substrate is pressed between the gravure cylinder and impression cylinder, which transfers the actual figure to the substrate. Gravure printing is used for very long runs. It is a fast technique and enables mass production. The thickness of the printed figure depends on the engravings on the gravure cylinder but also process parameters like print speed and pressure have an effect on the figure. In article [13], 20–60 μm gravure cells produced 4–7 μm ink layer. The substrate must be flexible in gravure printing because of the pressure which is needed to figure transfer [8, 13].

Ink jet is a fast and easy technique but it has few disadvantages. The printed ink layer is thin and the particles stirred into ink must be very small and uniformly spread. The particles must also be very good conductors. The inks are usually temperature dependent, which can also cause problems [8, 14].

If the conductive figure like an antenna pattern is fabricated by printing, the figure is usually cured. Curing can be done in convection oven but some inks cure in room temperature. When curing the patterns there are two important parameters: curing temperature and curing time. These have an effect on the conductivity of the pattern and they must be always taken in consideration when manufacturing tags.

Whether the conductive pattern is fabricated using any of the manufacturing techniques, the IC chip is attached to the complete conductive antenna pattern. There are different methods like flip chip joint and different strap joints to do that. Strap joint consists of an IC chip on a substrate with conductive pads, and the whole strap is attached to the antenna using, for example, conductive adhesives. Chip attachment also affects the antenna material selection, because the attachment process may need relatively high temperature. There are also many different IC chip types available and the chip selection must be considered for every application. The antennas may be laminated after chip attachment. If the tags were integrated to mass products with short lifetime, lamination might not be necessary [15, 16].

2. EXPERIMENTAL ARRANGEMENTS

Silver inks and screen printing were used to fabricate prototype antennas. Different paper qualities were selected as antenna substrate, because paper is cheap, environmentally friendly, and it is often used in packages. The prototype antenna was designed to work at UHF frequencies especially through paper. This was due to the increasing interest in paper industry to identify paper reels with passive UHF RFID technology [17]. In this case, the safest location for the tag would be on the reel core under the wounded paper. This means that the tag is then read through the thick paper layer. The maximum reliable read range (MRRR) of the tag prototypes was measured through paper reams and also in air, because in some cases, the identification might also be required in air. The measurement results of the ink-fabricated tag prototypes are then compared with the results achieved with copper and aluminium-fabricated tags studied in [4]. Figure 1 presents the geometry and dimensions of the bowtie antenna used in this study.

Conductivity and the behavior of three silver inks (see Table 3) on different papers were investigated before the actual tags were printed. With UHF frequencies, the ink layer in tag antennas does not need to be very thick, if the conductivity of the ink is high enough. Three different inks (inks

Table 1: Characteristics of different printing processes [8].

Process	Screen printing	Flexography	Gravure	Ink jet
Substrate	All	Papers Boards Polymers	Coated papers Boards Polymers	All
Ink film thickness (μm)	0,02–100	6–8	8–12	Depends on ink
Typical viscosity of ink (Pa.s)	0,1–10	0,01–0,1	0,01–5	0,01
Resolution (lines/cm)	50	60	100	60 (continuous) 250 (DOD)

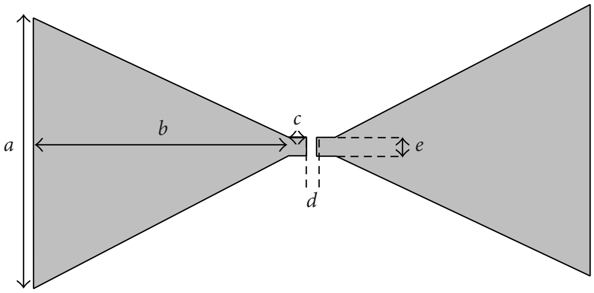
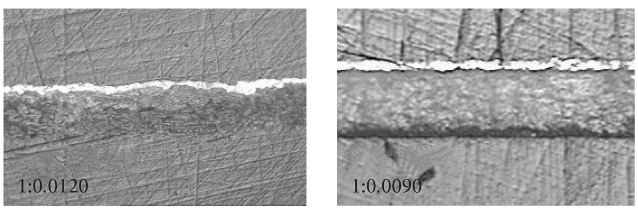


Figure 1: The geometry of the bow-tie antenna design. The dimensions are $a = 43$ mm, $b = 42.5$ mm, $c = 3.5$ mm, $d = 2$ mm, and $e = 3$ mm.



(a) (b)

Figure 2: Ink A (a) on paper 1 and (b) on paper 3.

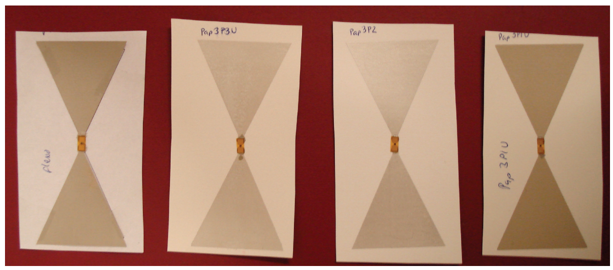


Figure 3: Fabricated prototype RFID bow-tie antennas.

(a) (b)

Figure 4: The measurement arrangements: (a) the tag fastened to a holder; and (b) the tag behind paper reams.

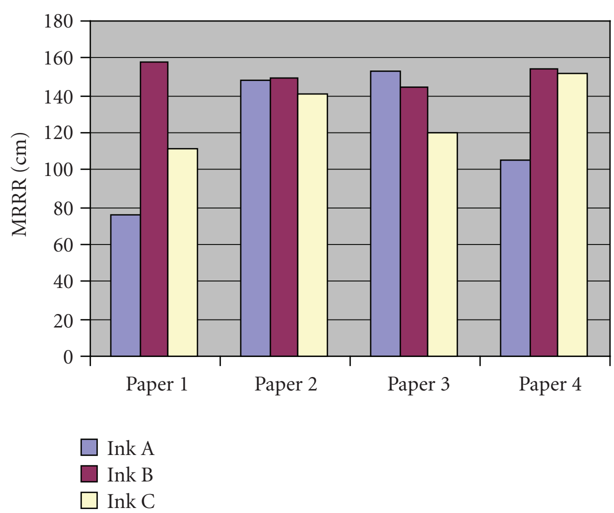


Figure 5: The average MRRR values, linearly polarized reader antenna.

A–C) were used on seven different paper substrates. The test pattern was a 11,5 cm $*$ 11,5 cm square and it was cured in convection oven after printing.

Based on these measurements, four different paper qualities (Papers 1–4) were selected as the antenna substrate (Table 2). Various papers are used in packages, so it was interesting to investigate different papers as the actual substrate of the tag. Paper 1 is a copy paper and it was selected because the ink was absorbed in the paper (see Figure 2(a)) and it would be interesting to see if the reading distance was shorter or the electrical contact with the chip was poor. Paper 2 and paper 3 were selected due to the good conductivity and thickness of the pattern on them for all inks which were used. Paper 2 is thicker than paper 3. Ink A on paper 1 is shown in Figure 2(a) and on paper 3 in Figure 2(b).

Paper 4 was selected because the surface of the paper is not smooth and the conductivity of the pattern was also good on this substrate for all three inks. The selected papers are introduced in Table 2.

Mesh of the stencil was selected based on the measurements which were done with the test pattern and also on

Table 2: Papers which were selected as antenna substrates and their characteristics.

Substrate	Description
Paper 1	Copypaper
Paper 2	Glossy cardboard (thickness 350 μm)
Paper 3	Multiart gloss 130 g/m^2 (glossy paper)
Paper 4	Chromopaper 120 g/m^2 (embossed coated paper)

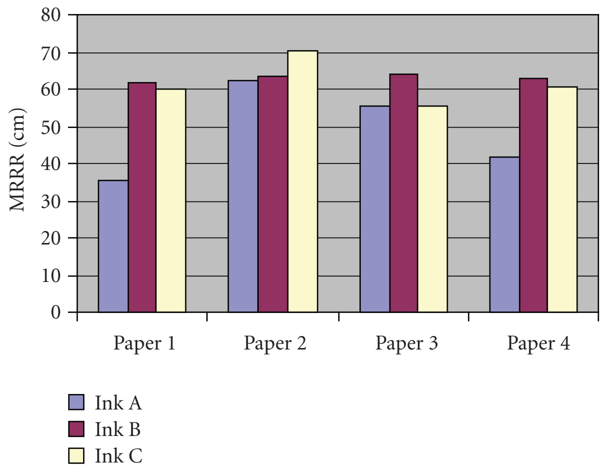


Figure 6: The average MRRR values, circularly polarized reader antenna.

penetration depth calculations. The penetration depth was calculated from the datasheets of the inks and they are illustrated in Table 3. The mesh of the stencil should produce a layer which is thick enough, but also not too thick because of price of the inks. The mesh was selected to be 62 T/cm (polyester stencil). The shore A hardness of squeegees was 75 which is the recommendation of the ink manufacturers. After printing, the antenna patterns were cured in convection oven in accordance with the instructions of the datasheets. These curing conditions and the characteristics of all three silver inks used in this study are illustrated in Table 3.

After curing the antenna patterns, the straps were attached to the antennas with conductive adhesive which was two-part silver epoxy. The adhesive cured in room temperature. The straps had EPC-Gen1-based microchip with 96 bit identification code. The tag prototypes are illustrated in Figure 3.

The feature which is measured in this research is called the maximum reliable read range, MRRR. The MRRR means the reading distance where the tag is continuously identified for at least one minute. The center frequency which was used in this study was 915 MHz and the RFID system was compliant with FCC regulations. The reader unit supported EPC Class 1 Generation 1 standard. Linearly polarized and circularly polarized reader antennas were used in these measurements. The gain of both of the reader antennas was 6 dBi. The read range measured with linearly polarized reader antenna is heavily dependent of the antenna orientation and the tag should thereby be aligned with the reader antenna polarization plane. When using circular polarization, the read range is not so dependent on the tag position, because the polarization plane rotates with the electric field vectors. The disadvantage of circular polarization is the 3 dB power loss which appears due to polarization mismatch when the tag antenna is linearly polarized and shortens the reading range. The MRRR was first measured in air, because the air is the most common medium for RFID systems and in most cases reliable identification might be required also in air. The tag antenna was attached to a wooden holder and it was isolated with polystyrene from the wood, so that the wood would not interfere the measurements. The tag fastened to the wooden holder is shown in Figure 4(a).

The movable holder with the tag was moved away from the reader antenna until the distance where the tag still is continuously identified. This distance (MRRR) between the tag and reader antenna was then measured.

The power losses considering the circular polarization were calculated after MRRR measurements. The power loss presents the relation of two radiation powers. In this case, the power loss is calculated using formula (1), where $\mathrm{MRRR_{LP}}$ means the MRRR measured using linearly polarized reader antenna and $\mathrm{MRRR_{CP}}$ means the MRRR measured using circularly polarized reader antenna. The relation of the read ranges is the same as the relation of radiation powers and therefore it can be used to calculate the power losses,

$$\text{Power loss (dB)} = 10\lg\frac{P_{\mathrm{CP}}}{P_{\mathrm{LP}}} = 10\lg\frac{\mathrm{MRRR_{CP}}}{\mathrm{MRRR_{LP}}}. \qquad (1)$$

3. RESULTS AND DISCUSSION

First measurement was maximum reliable read range in air. The MRRR values were measured for the tag antennas printed with all three inks on the four selected paper substrates. There was two of each material combination. The MRRR values in air and the power loss caused by use of the circular polarization are presented in Table 4. LP stands for linear polarization and CP stands for circular polarization.

The best MRRR for printed prototype tags was 158 cm (linear polarization) for the tag printed with ink B on paper 1 and paper 4. The best MRRR using circularly polarized reader antenna was 80 cm for the tag printed with ink C on paper 2. The average MRRR was 134 cm (linear polarization) and 57 cm (circular polarization). MRRR measurements have been done for same size copper bow-tie antennas on FR4 laminate and aluminium bow-tie antenna on plastic foil. MRRR for copper tag was 139 cm with linearly polarized reader antenna and 65 cm with circularly polarized reader antenna and 89 cm (linear polarization) and 35 cm (circular polarization) for aluminum tag. So, the reading performance of silver-ink antennas was at least as good [4].

The straps were attached to the copper tags and aluminum tags without conductive adhesive, which might cause differences between the copper tags and printed tags. There were differences also between individual printed tags due to the printing process used and due to chips, which are also individuals. The chip attachment may also cause differences. All tags did not work, because the chips might have been broken or there might also have been short circuits due to

Table 3: The characteristics of the silver inks.

Ink	Curing temperature (°C)	Curing time (min)	Manufacturers description	Viscosity (P)	Conductivity (MS/m)	Penetration depth (μm) (for 915 MHz)
A	120	30	Polymeric ink consisting of silver particles and thermoplastic resin	30–50	1,7	13
B	120	30	Polymeric thermoplastic silver ink	10–20	2,8	10
C	85	20	Polymeric silver-filled ink with proprietary additive	180	3,1	10

Table 4: The MRRR values and power losses measured in air.

Substrate	MRRR, LP reader antenna (cm)	MRRR, CP reader antenna (cm)	Power loss (dB)
Paper 1	64	28	−3,5
Paper 1	88	43	−3,1
Paper 2	149	60	−3,9
Paper 2	147	65	−3,5
Paper 3	152	56	−4,3
Paper 3	154	55	−4,4
Paper 4	137	63	−3,4
Paper 4	73	20	−5,6
Paper 1	158	62	−4,1
Paper 1	Does not work	Does not work	Does not work
Paper 2	146	64	−3,6
Paper 2	152	63	−3,8
Paper 3	144	64	−3,5
Paper 3	Does not work	Does not work	Does not work
Paper 4	151	63	−3,8
Paper 4	158	63	−3,9
Paper 1	111	60	−2,7
Paper 1	Does not work	Does not work	Does not work
Paper 2	138	80	− 2,4
Paper 2	144	61	−3,7
Paper 3	145	64	−3,6
Paper 3	96	47	−3,1
Paper 4	153	59	−4,1
Paper 4	151	62	−3,8
			Average: −3,7

Table 5: The best MRRR values measured with linearly polarized reader antenna.

Substrate	Ink	MRRR (cm)
Paper 1	B	158
Paper 2	B	152
Paper 3	A	154
Paper 4	C	158

Table 6: The best MRRR values measured with circularly polarized reader antenna.

Substrate	Ink	MRRR (cm)
Paper 1	B	62
Paper 2	C	80
Paper 3	B and C	64
Paper 4	A and B	63

the chip attachment. The average MRRR values for printed bow-tie antennas on different paper substrates are shown in Figures 5 and 6.

All inks worked well particularly on paper 2, but all paper substrates were suited to be antenna substrates based on the measurements. The best MRRR values on different paper substrates are shown in Table 5 with linearly polarized reader antenna and in Table 6 with circularly polarized reader antenna.

The MRRR values which are measured with linearly polarized reader antenna are approximately two times the MRRR values measured with circularly polarized reader antenna. This is due to the 3 dB power loss which is caused by the polarization mismatch with the circularly polarized reader antenna. The power loss in measurements was not exactly 3 dB mostly because of the measurement arrangements. Multipath propagation was possible, because the room was not completely RF anechoic. The circularly polarized reader antenna is in practice slightly elliptically polarized which also affects the measurement results. The wooden holder might not be right in line with the reader antenna all the time, because the holder was on wheels and there were no rails on the floor. These distractions concern also the measurements through paper reams as shown in Table 8.

The prototype bow-tie tag antenna was designed to work through paper due to interest in applying passive UHF RFID in paper industry. In addition, for example, in identification of different products and packages, there might be a need to read the tag through a dielectric medium like paper. This is why the tag was designed to operate in paper and the MRRR was measured when the tag was behind paper reams. The length of the bow-tie antenna is approximately the half wavelength of the 915 MHz electromagnetic wave when it propagates through paper [4]. Bow-tie antennas are relatively broadband, and thereby the tested tag antenna operates sufficiently well also in air [3]. However, to optimize the performance of the antenna design in air, the geometry of the antenna has to be altered to better correspond to the wavelength of the electromagnetic wave in air.

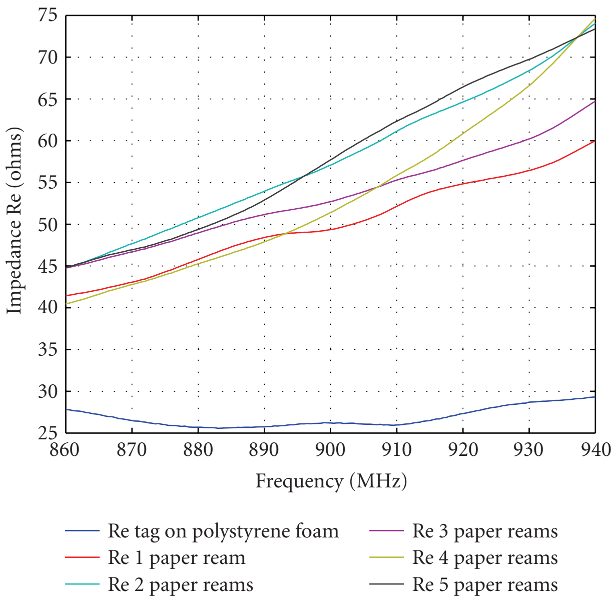


Figure 7: Real part of the bow-tie antenna's input impedance.

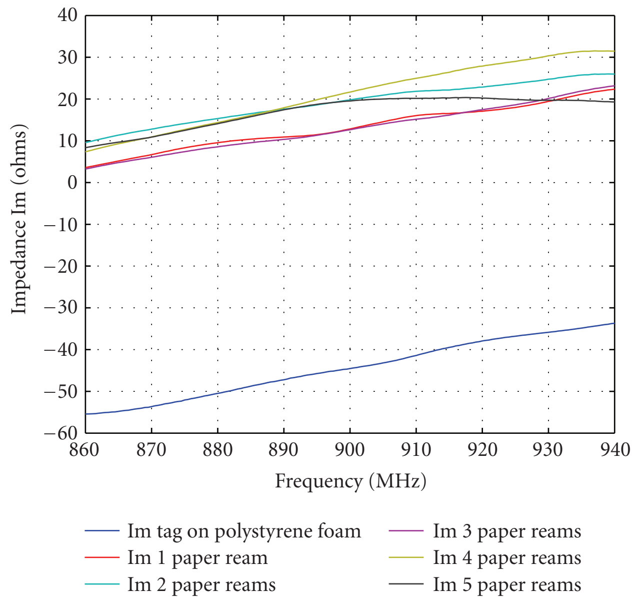


Figure 8: Imaginary part of the bow-tie antenna's input impedance.

In addition, impedance matching of the antenna design to the input impedance of the IC chip is essential for good tag performance. Typically, the complex input impedance of an RFID IC is highly reactive. In ideal case, the input impedance of the tag antenna is the complex conjugate of the IC input impedance for maximum power transfer [1].

To study the input impedance behavior of the bow-tie antenna design, its input impedance was measured as a function of frequency with a network analyzer in air and under 1–5 paper reams. Figure 7 presents the real part of the antenna's input impedance and Figure 8 presents the imaginary part of the input impedance. The results show that the real part of the input impedance increases when paper reams are added on the antenna design. In addition, when paper reams are added the imaginary part of the input impedance changes from capacitive to inductive. In addition to the dimensions of the antenna design, which are optimized for functioning through paper, the change of the imaginary part from capacitively to inductively reactive explains the increased read ranges through paper. The impedance matching of the antenna design could be further improved by increasing the inductive reactance component and possibly lowering the real part of the input impedance. This can be done with, for example, matching stubs that are added to the antenna's input structure.

Reams of copy paper were used in the measurements and one to five reams were added in front of the tag. Thickness of one ream was 55 mm. The MRRR was measured every time when a ream was added. Figure 4(b) illustrates the tag behind paper reams. The MRRR measurements were performed the same way than the measurements in air. The MRRR values behind paper are illustrated in Table 7.

The power losses concerning circular polarization are presented in Table 8. One disturbing factor is additional paper-air interfaces, which arise when the paper reams are added in front of the tag. It was difficult to attach the reams closely with each other, especially when only 1 or 2 reams were added. This affects the measurement results. The power loss decreases slightly when paper reams are added. This is due to the improved impedance matching of the bow-tie antenna to the input impedance of the IC when it operates through paper.

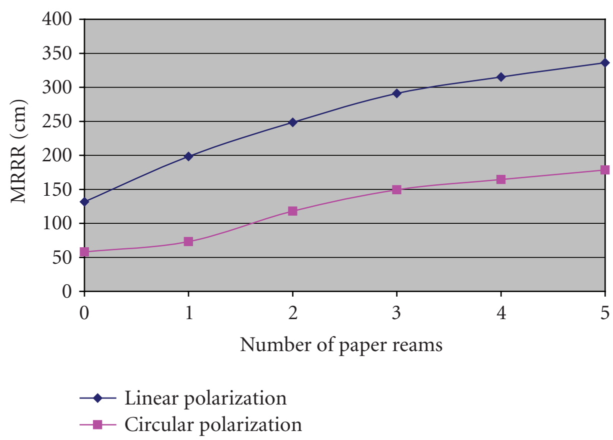


Figure 9: The effect of paper reams on MRRR.

The radiation pattern of the bow-tie antenna changes from the form of a typical omnidirectional dipole antenna radiation pattern when reams of paper are added in front of the tag [18]. Adding paper reams improved the MRRR whether linearly or circularly polarized reader antenna was used, as shown in Figure 9.

The tag antennas start to direct the radiation toward the reader (the direction where paper reams are added) [18]. This is due to the effect of paper as a dielectric material on

Table 7: The effect of paper reams in front of the tag on the MRRR values.

Tag		MRRR (cm)											
		Linearly polarized reader antenna The amount of paper reams						Circularly polarized reader antenna The amount of paper reams					
Substrate	Ink	0	1	2	3	4	5	0	1	2	3	4	5
Paper 1	A	88	109	170	237	270	265	43	57	62	98	124	141
Paper 2	A	147	209	279	317	328	328	65	67	95	162	180	175
Paper 3	A	154	188	258	322	349	390	55	62	133	163	172	178
Paper 4	A	73	101	145	187	227	226	20	49	63	88	111	127
Paper 1	B	158	160	271	320	362	371	62	76	129	164	174	191
Paper 2	B	152	229	275	323	348	385	63	91	142	165	180	200
Paper 3	B	144	256	275	278	326	390	64	75	157	165	178	207
Paper 4	B	158	213	276	319	336	353	63	76	138	157	165	184
Paper 1	C	111	213	273	306	325	345	60	92	135	162	161	181
Paper 2	C	144	234	280	327	344	380	61	76	138	157	185	208
Paper 3	C	96	146	185	268	275	316	47	58	66	135	150	190
Paper 4	C	151	232	281	323	347	378	62	90	142	165	208	208

Table 8: The power losses related to measurement results presented in Table 7.

Tag		Power loss (dB)				
		The amount of paper reams				
Substrate	Ink	1	2	3	4	5
Paper 1	A	−2,8	−4,3	−3,8	−3,4	−2,7
Paper 2	A	−4,9	−4,6	−2,9	−2,6	−2,7
Paper 3	A	−4,8	−2,8	−3	−3,1	−3,4
Paper 4	A	−3,1	−3,6	−3,3	−3,1	−2,5
Paper 1	B	−3,2	−3,2	−2,9	−3,2	−2,9
Paper 2	B	−4	−2,9	−2,9	−2,9	−2,8
Paper 3	B	−5,3	−2,4	−2,3	−2,6	−2,8
Paper 4	B	−4,5	−3	−3	−3,1	−2,9
Paper 1	C	−3,6	−3	−2,8	−3,1	−2,8
Paper 2	C	−4,8	−3,1	−3,2	−2,7	−2,6
Paper 3	C	−4	−4,4	−3	−2,6	−2,2
Paper 4	C	−4,1	−2,9	−2,9	−2,2	−2,6
Average		**−4,1**	**−3,4**	**−3**	**−2,9**	**−2,4**

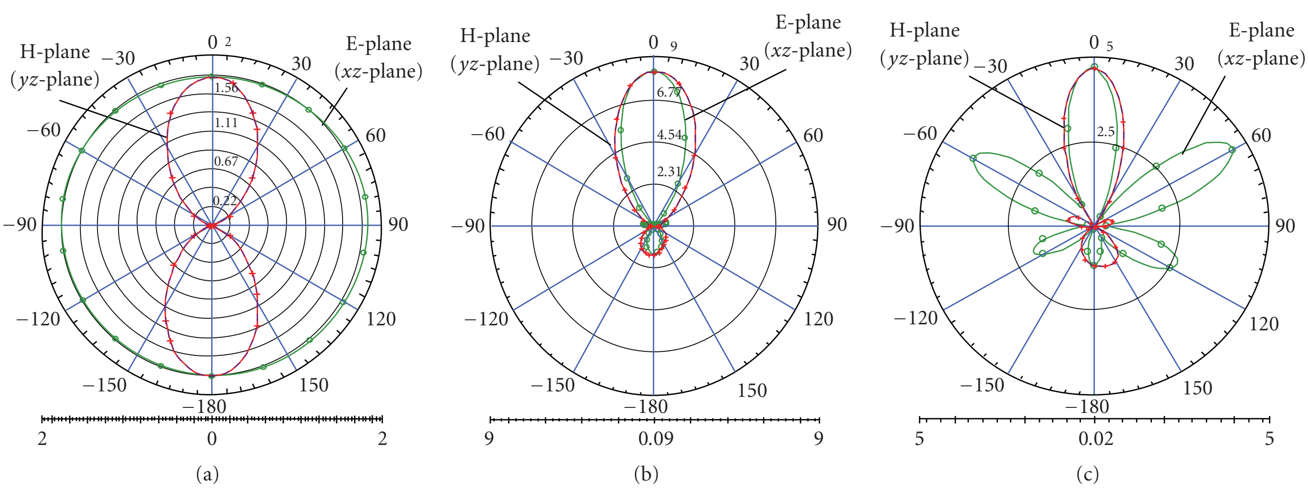


Figure 10: The radiation patter of a bow-tie tag: (a) in air, (b) behind three paper reams, and (c) behind five paper reams [18].

Table 9: The best MRRR values behind five paper reams measured with linearly polarized reader antenna.

Substrate	Ink	MRRR (cm)
Paper 1	B	371
Paper 2	B	385
Paper 3	A and B	390
Paper 4	C	378

Table 10: The best MRRR values behind five paper reams measured with circularly polarized reader antenna.

Substrate	Ink	MRRR (cm)
Paper 1	B	191
Paper 2	C	208
Paper 3	B	207
Paper 4	C	208

the radiation pattern. More than five reams are not added because after five reams, the wavelength of the 915 MHz electromagnetic waves is reached in paper when the dielectric constant ε_r of copy paper is considered to be 3. When the thickness of paper exceeds one wavelength, the paper reams mostly increase the attenuation rather than affect the radiation properties of the tag antenna itself. Figure 10 presents the radiation pattern of a bow-tie tag investigated in article [18]. When three paper reams are added in front of the tag, the antenna substantially directs the radiation and when five paper reams are added, side lobes appear. The antenna which was investigated in article [18] is a copper tag and it is bigger than the bow-tie antenna used in this article. Still it gives a good idea of the behavior of the bow-tie tag generally.

The best MRRR values on different paper substrates are shown in Table 9 for linear polarized reader antenna and Table 10 for circularly polarized reader antenna. All of these values were measured after adding five paper reams in front of the tag.

All inks and paper substrates worked sufficiently well when the tag was read through paper. Based on the measurements, the printed antennas would be suitable for radio frequency identification also in challenging applications, such as paper reel identification.

The price of inks is one of the biggest costs when printing RFID tags. This is why further investigation must be done to reduce the costs due to the ink. In articles [19, 20], the amount of ink was investigated. The bow-tie antennas were made of conductive grid or the conductive wires were only on the outlines of the bow-tie tag (wire approximation of the bow-tie tag). Still the simulated radiation properties of the bow-tie antenna were quite the same for wire approximation bow-tie antenna than a regular one. The gridded bow-tie antenna had lower radiation efficiency than a regular bow-tie antenna, but material savings were accomplished [19, 20].

4. CONCLUSIONS

This paper presents an analysis of silver ink bow-tie RFID tag antennas printed on paper substrates. The substrate has an effect on printed RFID antennas. The ink may be absorbed in the substrate if the substrate is porous like paper. Four different paper substrates and three silver inks were selected as antenna materials. The maximum reliable read range in air for printed tags was quite the same as the values reported elsewhere for copper tag on FR4 laminate and aluminum tag on plastic foil. The tags worked well enough also in air although they were designed to operate through paper. This is important in some cases where identification is required both behind dielectric medium and in air.

The bow-tie tag was designed to be read through paper. The MRRR increased when reams of copy paper were added in front of the tag because the electrical length of the antenna was matched the half wavelength of 915 MHz electromagnetic wave propagating through paper. The best MRRR was measured through five paper reams. Because the tag identification behind paper reams was successful in this study, it might be possible to achieve cost savings by printing the tags directly on packages where tags also may be behind thick stacked cardboard or stacked paper layers. In addition, according to the results, the printing technique could also be used in paper industry applications where paper reel tags are affixed to the reel core and read through paper that is wounded around the core.

The MRRR values which were measured with circularly polarized reader antenna were approximately a half of the values measured with the linearly polarized reader antenna. This is due to the 3 dB power loss caused by the polarization mismatch between the tag and the reader antenna. The power loss in measurements was not exactly 3 dB mostly because of the measurement arrangements and the tag antenna properties. This might be the case in the real identification environment also. The orientation of the tag in front of the reader antenna can be random when using circular polarization, which is important in many applications.

The ink layer is thicker if the substrate does not absorb the ink. Still the absorbed ink is also conductive and in tests the printed antennas worked well on porous copy paper. Actually, all papers which were used in tests were suitable as antenna substrate and all three inks worked well. Although the antennas worked well in read-range measurements, there were differences between individual tags due to the printing process, IC chips, and IC chip attachment.

Based on the measurements, printed RFID tags which work on UHF frequencies would be suitable for many applications. Printing tag antennas on paper is environmentally friendly, simple, and fast process which can lower the manufacturing costs of the tags. The tests encourage carrying out more research to integrate the tags to packages and to further reduce tag prices. The effects of manufacturing parameters and different environments would be interesting to examine closely. Also different inks, printing techniques, antennas, and their cost effects should be examined. More antenna design and different geometries would be interesting to investigate to improve read ranges both in air and behind dielectric medium. The object which is to be identified might also cause other demands on the tags. For example, flexibility of the tag antenna might be necessary. These demands have to be taken into consideration in each separate case.

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