Identification of Industrial Paper Reels with Passive UHF RFID

Leena Ukkonen, Lauri Sydänheimo, and Markku Kivikoski

Tampere University of Technology, Institute of Electronics, Rauma Research Unit
Kalliokatu 2, 26100 Rauma, Finland
`leena.ukkonen@tut.fi`
`http://www.rauma.tut.fi`

Abstract. In paper industry there is a strong need for an identification system that would carry on the identification code of a specific reel throughout its life cycle. Application of passive ultra-high frequency (UHF) radio frequency identification (RFID) systems in paper industry requires novel tag antenna designs for identification of paper reels. By attaching the tag antenna to the reel core between the core and the wrapped paper the identification data of a particular reel can be stored throughout its whole life cycle. However, paper attenuates the electromagnetic wave, and therefore energy harvesting for the tag's microchip and backscattering of the identification data back to the reader is challenging. In addition, the wavelength of electromagnetic wave decreases when it propagates through paper, which affects the electrical dimensions of the tag antennas. In this paper we analyze the challenges in identification of paper reels with passive UHF RFID technology, and present an evolutionary tag antenna design for passive UHF RFID of paper reels. This C-tag antenna can be identified omnidirectionally around an industrial paper reel.

1 Introduction

In paper industry there is an urging need for an automated identification system, which would carry on the identification code of a particular reel throughout the whole life cycle and supply chain of paper reels. At the moment, when barcode identification systems are used, the identification code and thereby the information about the specific reel disappears when the wrapping and the barcode are removed. However, when radio frequency identification (RFID) systems are used the safest place for the tag would be on the surface of the reel core between the core and the paper. This way the identification code is restored throughout the lifecycle of the reel from paper mill to the end user for example in printing companies. RFID systems would benefit paper industry by providing real time information for example about handling locations of the reel. Also, since the origin of the reel is known throughout its life cycle, the use of RFID systems would improve the quality control. The overall cost reductions due to using RFID would result in the more efficient and automated identification and improved quality control throughout the whole supply chain and life cycle of paper reels [1, 2].

Paper reels consist of a cylinder-shaped core, which is made of hard 15 mm thick cardboard, and the paper that is wrapped around the core. Figure 1 presents the structure of the paper reel. The outer diameters (*d*) of cores vary typically from 105 mm to 300 mm. The paper layer thickness (*t*) varies typically from 500 mm to 700 mm. The overall diameter (*D*) of the reel is therefore $D = 2t + d$. The length of the reel (*l*) is typically between 0.30 m and 2.50 m. The placement of the tag between the core and the paper sets challenges for passive ultra-high frequency (UHF) RFID. Tag microchips in passive RFID systems do not have an internal source of energy. Passive tags get all the energy for functioning from the electromagnetic radiation emitted by the reader. The communication in passive UHF RFID systems is based on backscattering: reader transmits energy, commands and data to tag which then responds by backscattering its identification data back to the reader [3].

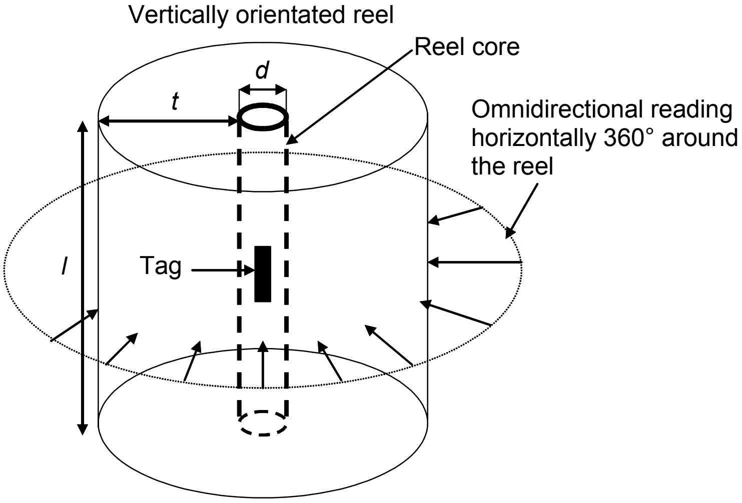

Fig. 1. Structure of a paper reel and the concept of omnidirectional reading.

Due to the placement of the tag on the reel core, the tag's antenna has to be designed to operate through paper. When an electromagnetic wave propagates through paper, its wavelength, speed and amplitude decrease. The decreased wavelength is the ratio of the free-space wavelength (λ_0) and the square root of the dielectric constant (ε_r) of paper and affects the electrical dimensions of the tag antenna inside the reel [4]. Thereby the tag antenna has to be tuned to radiate at the right frequency when it is placed between the core and the paper. In addition, since paper attenuates the electromagnetic wave the tag antenna must have enough surface area to harvest energy for the microchip and to backscatter its identification data back to the reader.

The dielectric constant (ε_r) of dry paper varies typically between 2 and 4 depending on density, filler content, fiber furnish etc. Fillers, for example $CaCO_3$ and kaolin, increase the density of paper, and also the dielectric constant of fillers is usually higher than the dielectric constant of food fibres. For example, the dielectric constant of $CaCO_3$ is approximately 8.5. Due to these two issues, fillers increase the dielectric constant of paper. Also, the loss tangent of paper ($\tan\delta$), and thereby the dielectric losses of paper, increases linearly with density. Dielectric properties of paper are also affected by the moisture in paper. The moisture content of paper is typically 3 – 7 %, and it significantly increases the dielectric losses and thereby the attenuation of electromagnetic wave [5]. The dielectric properties and the moisture content of different paper qualities are various, and therefore it is important to design a tag antenna design that would have good performance with various paper qualities.

Reflections of electromagnetic wave on air-paper boundary increase the complexity of analyzing the RFID of paper reels. It has been observed that paper acts as a dielectric lens when an electromagnetic wave propagates over the boundary of air and paper [4]. Also, since the structure of paper is inhomogeneous, reflections and refractions of electromagnetic wave occur also inside the paper layer that is wrapped around the core. The tag antenna radiation pattern should therefore be optimized to diminish the effects of reflections and refractions of electromagnetic wave.

In addition to the ability to read the tag through paper, one of the biggest challenges has been developing a tag antenna that would be readable omnidirectionally. This means that the reel can be identified horizontally 360° around it. The concept of omnidirectional reading is explained in Fig. 1. This feature is crucial for example in lift truck handling of the reels. Also, when the tag can be read omnidirectionally the reels can be identified at all occasions for example inside the paper mill with only one reader antenna instead of using two or more reader antennas in a gate configuration.

2 The C-Tag Antenna Design for Paper Reels

In previous studies [2] bow tie-type antennas have shown promising performance when stacked inside paper layers. Bow tie antennas are broadband dipole-type microstrip antennas that can be used in various applications of wireless communications [6, 7]. We have tested bow tie-type tag antennas, which are very similar to the commercially available dipole-type tag antennas, inside industrial paper reels so that the tag has been attached to the reel core and the paper has then been wrapped around it. Figure 2 presents the geometry of a bow tie tag for paper reel identification. The overall length of the antenna is 80 mm, which corresponds to approximately half-wavelength of 866 MHz inside a paper layer with ε_r of approximately 3. The diameter of the tested paper reel was 1220 mm, and the paper quality was coated offset printing paper. The read range was measured with Alien Technology's European 866 MHz 2 W effective isotropic radiated power (ERP) reader unit (serial number ALR-8780-05-00163, software version 2.12.01) and a linearly polarized reader antenna. Figure 3 presents the measurement equipment, the tested paper reel and the measurement directions. In field testing in the paper mill the reel was in horizontal orientation for practical reasons. The read range measured from the outside surface of the paper reel when the reader antenna and the tag antenna were aligned was 1.40 m, which is the distance in free air from the paper layer outside surface to the reader antenna. Considering that the tag is read through 558 mm thick paper layer, the read range is sufficient. However, the tag cannot be read omnidirectionally 360° around the paper reel. The tag can be identified at 990 mm from the paper layer surface at 90° angle from the tag antenna. Therefore, a novel antenna design has to be developed to achieve omnidirectional readability, which cannot be achieved with the tested bow-tie tag antenna or any commercially available dipole-type tags.

Fig. 1. Structure of a bow-tie antenna that is designed to operate through paper.

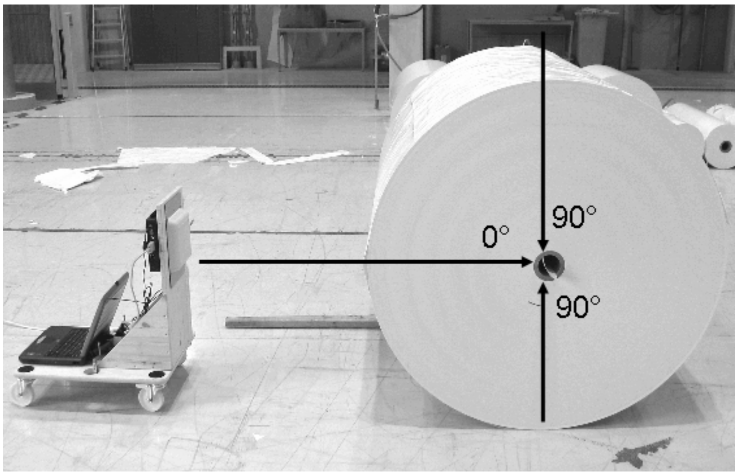

Fig. 3. RFID measurement system, the measured paper reel and the measuring directions at the paper mill.

Based on the previous observations and the need for an omnidirectional tag antenna the C-tag antenna was developed. The geometry and dimensions of the C-tag are presented in Fig. 4. It is a modification of a bow-tie antenna with larger area and a length that is proportional to the wavelength of the electromagnetic wave inside paper or cardboard. The identification data-containing microchip is attached in the middle of the antenna design over the 2 mm gap between the strips on the right in Fig. 4. There is also a matching structure, which is the 36 mm slot, for the microchip to increase the inductive reactance component of the antenna's input impedance and that way to better match the microchip to the antenna structure. The microchips used in this research had 1200–j145 Ω input impedance and 96 bit identification code. The microchips were mounted on a plastic substrate and had metallic pads to make attaching them to the tag antenna designs easier. Figure 5 shows the C-tag in its place mounted on the reel core. The tag forms a shape of C when mounted around the core.

Reel core diameters vary from 75 mm to 300 mm, and the C-tag antenna dimensions can be optimized for the different core diameters.

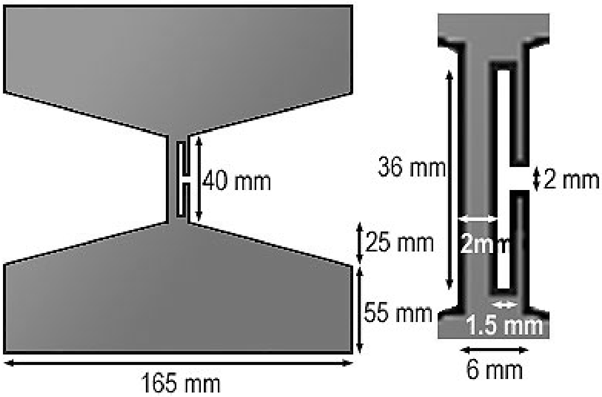

Fig. 4. Geometry and dimensions of the C-tag antenna.

Fig. 5. C-tag antenna mounted on the reel core.

3 Read Range Measurements

The performance of the C-tag antenna was optimized and verified with read range measurements. In these measurements the antenna design was attached to the reel core and identified through paper layers of various thicknesses. The testing was carried out in both laboratory conditions and industrial paper mill environment. In laboratory testing we got information about the tags radiation pattern and readability through paper. These results were used to evaluate the C-tag antenna design before testing with industrial paper reels.

We used the European 866 MHz reader unit presented in Chapter 2 with 2 W ERP based on European Telecommunications Standards Institute (ETSI) standards and a linearly polarized reader antenna in the testing in both laboratory and paper mill environments. Linearly polarized reader antennas are suitable for paper and reel identification because in paper industry environment and other locations where reels are handled the position and orientation of the reels, and thereby the orientation of the tag antenna, is never arbitrary. Thereby, aligning the polarizations of the linearly polarized reader and tag antennas is easy.

The advantages of using linearly polarized reader antennas includes smaller polarization losses and thereby longer read ranges that would be achieved with circularly polarized reader antennas [8]. Also, since a circularly polarized electromagnetic wave propagates rotating like a spiral, the polarizations of a circularly polarized reader antenna and a linearly polarized tag antenna do not match throughout the whole rotation circle of the electric field vectors. According to [8], this also shortens the read ranges achieved with circularly polarized reader antenna. In addition, circularly polarized antennas are more sensitive to the external noise in the environment.

3.1. Testing in Paper Mill Environment

In the field testing the tag antenna was first attached to the reel core so that it was placed in the middle of the core length, and then the paper was wrapped around it. Before the paper was wrapped around the tag antenna and the core, the maximum read range in air was measured. The C-tag antenna on the reel core was identified from 7.10 m when the antenna design was in line-of-sight with the reader antenna. The measurement equipment is presented in Fig. 3. The paper quality was coated offset paper, and the paper layer thickness was 570 mm. The reel core outer diameter was 175 mm. The overall diameter of the paper reel was thereby 1315 mm. Coated papers are more attenuating than for example copy paper because of the larger amount of fillers and coating materials. The reel was measured from 16 testing points around the reel. The reader antenna was in line-of-sight direction to the testing points. At each point the maximum read range from the paper reel outside surface was measured. The continuous identification around the reel was verified by testing the tag identification also between the measuring points when the reel was rolled to the next measuring position. The omnidirectional measurement was replayed three times to guarantee the results. Figure 6 presents the maximum read ranges measured around the paper reel from the outside surface of the paper layer. The results are mean values of the measured read ranges. S in Fig. 6 indicates the location of the microchip, and thereby the centre position of the tag antenna design. It can be observed that the paper reel is identified omnidirectionally around it with read ranges from the paper reel surface varying from 0.36 m to 1.26 m. The read ranges in parenthesis are measured from the reel centre and they vary from 1.02 m to 1.92 m.

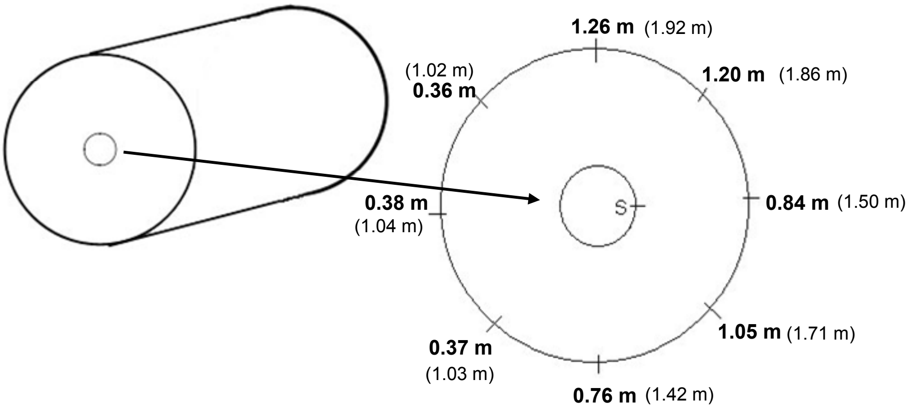

Fig. 6. Omnidirectional read range measurement results of an industrial paper reel.

4 Conclusions and Future Work

In this paper the challenges in passive UHF RFID of paper reels and an omnidirectional C-tag antenna for passive UHF RFID of paper reels is analyzed and presented. To our best knowledge, the C-tag antenna is the first tag antenna that can be identified omnidirectionally through a paper reel with standardized RFID equipment. This tag antenna design can be used with both coated and uncoated paper qualities, and it is easily applicable also on different reel core diameters.

In the future, there still are a number of challenges that have to be confronted and solved. First, the tag antenna design will be further developed to achieve longer read ranges and even more stable operation from all the directions around the paper reel. The goal is to achieve at least 0.50 m read range omnidirectionally from the paper reel surface. Secondly, an omnidirectionally readable tag antenna will be developed also for identification of cardboard reels. The C-tag antenna has been preliminarily tested in cardboard reel identification, and the results have been promising. Thirdly, since various centre frequencies and transmission power levels are used in RFID systems in different continents, the tag antenna should be readable within the whole UHF RFID band from 866 MHz to 950 MHz. The development of this global paper reel tag also includes finding the best possible dimensioning to guarantee the identification of different paper qualities with varying dielectric properties, moisture content and reel core diameters.

Also, the industrial environment sets challenges for the performance of the paper reel tag and the whole RFID system. The functioning of the paper reel tag has to be confirmed also in the harshest conditions, for example in cold outdoor warehouses of paper reels where the temperatures are far below 0 °C. In addition, developing an integrated reader unit for paper reel lift trucks is a necessity in applying RFID in paper industry.

References

[1] MICHAEL, K. and MC CATHIE, L., The Pros and Cons of RFID in Supply Chain Management, Proceedings of the IEEE International Conference on Mobile Business, 2005, pp. 623–629.

[2] SCHAFFRATH, M., UKKONEN, L., SYDÄNHEIMO, L., and KIVIKOSKI, M., RFID Antenna Designs for Paper Industry Applications: Passive Bow-Tie Transponder Performance Analysis, Proceedings of the 2nd IASTED International Conference on Antennas, Radar and Wave Propagation, Banff, AB, Canada, July 2005, pp. 348–353.

[3] FINKENZELLER K., RFID Handbook, 2nd Edition, John Wiley & Sons, United Kingdom, 2003, pp. 7–59.

[4] SYDÄNHEIMO, L., Studies towards Advanced Mobile Systems in Industrial Applications, Ph.D. thesis, Tampere University of Technology, TUT Publication 574, 2005, pp. 46–58.

[5] SIMULA, S., VARPULA, T., IKÄLÄINEN, S., SEPPÄ, H., PAUKKU, A., and NISKANEN, K., Measurement of the Dielectric Properties of Paper, Journal of Imaging Science and Technology, Vol. 44, Issue 1, 1999, pp. 472–477.

[6] KUMAR, G. and RAY, K. P., Broadband Microstrip Antennas, Artech House, United States, 2003.

[7] ANDRENKO, A. S., Comparative Study of Wide Band Properties of Planar Solid and Strip Fractal Bow Tie Dipoles, Proceedings of the IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics, 2005, pp. 178–181.

[8] SYDÄNHEIMO, L., UKKONEN, L., and KIVIKOSKI, M., Effects of Size and Shape of Metallic Objects on Performance of Passive Radio Frequency Identification, The International Journal of Advanced Manufacturing Technology, IJAMT, Springer, 2006. (In press)