Importance of Computational Electromagnetic Modeling in the Development of RFID Tags for Paper Reel Identification

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***Abstract*─** Development of the RFID tag for paper reel identification in industrial environment is discussed. Paper reel supply chain and history of the development of the presented antenna design is explained. Modeling of the paper reel tag is discussed and a case study of tag antenna − paper reel co-design is presented.

***Index Terms*─** UHF RFID, paper reel identification, tag antenna design.

I. INTRODUCTION

As the use of passive ultra-high frequency (UHF) radio frequency identification (RFID) systems emerges also the number of challenging applications increases. One of the most challenging applications for passive UHF RFID systems is identification of industrial paper reels. In paper industry there is a need for an automated identification system that would carry on the identification code of a specified reel throughout its life cycle. Nowadays when barcode identification systems are used in paper reel identification the identification code disappears when the wrapping paper and the barcode are removed. On the contrary, the RFID tag would be attached on the core of the reel and thereby the reel would be identifiable throughout its life cycle as long as the reel is in use. Since the tag will be attached on the core of the reel the tag has to be read through paper which attenuates the electromagnetic wave. As a dielectric material, paper also affects the electrical dimensions of the tag antenna design [1, 2]. Typically, the dielectric constant (ε_r) of paper varies from 2 to 4 [2] based on the paper quality and environmental conditions. Thereby, the challenges in paper reel identification are due to the functioning principle of passive UHF RFID systems, the attenuating properties of paper and also the fact that the paper reel should be identified omnidirectionally [3].

Figure 1 presents the components of a passive UHF RFID system. Passive UHF RFID systems use electromagnetic waves in coupling and communication between reader unit and tag. The reader sends a continuous wave (CW) signal to the tag to activate its microchip, followed by commands that are modulated to the CW signal. The tag responds with its identification code using backscattering of the modulated electromagnetic wave. There is no internal source of energy in the tag's microchip, and it gets all the energy it needs to function from the electromagnetic wave transmitted by the reader.

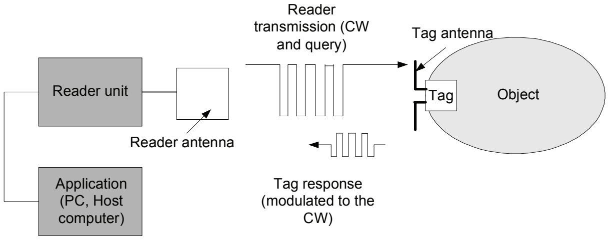

Fig. 1. Components of a passive UHF RFID system.

The communication between the reader and the tag is achieved by the tag switching its load impedance, which modulates the radar cross section (RCS) of the tag. The RCS of a scattering target is the equivalent area of the target based on the target reradiating or scattering the incident power. RCS can be described as a representation of how effectively a target can scatter the incident

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power. Therefore, the RCS of a target is not necessarily equivalent to its physical size.

When the target is a loaded antenna, such as a tag antenna with an integrated circuit (IC) chip, the RCS can be altered by terminating the antenna with different load impedances. Typically, in RFID tags, the impedance of the IC chip is altered between matched and mismatched states. In the matched state the input impedance of the tag antenna and the IC chip are complex conjugate matched and therefore maximum power is transmitted through the antenna to the IC chip. In the mismatched state the impedance of the IC chip and the tag antenna are not complex conjugate matched and therefore the electromagnetic wave from the reader antenna will be reflected back. This way the tag's binary identification code is modulated and scattered back to the reader unit. The modulating depth of the RCS also affects the tag's read range: deeper RCS modulation results in longer read range [4, 5]. This may be essential in the most challenging applications, such as in paper reel identification, where significant backscattered signal attenuation is present.

In most cases the limiting factor for the read range achieved with passive UHF RFID systems is the amount of power delivered to the IC chip, i.e. the threshold power of the tag. In the case of paper reel identification, this requirement becomes crucial due to the attenuating properties of paper.

In terms of electromagnetic modeling and tag antenna design, paper reels are complex objects due to varying material properties and boundaries within the object. To verify the performance of the paper reel tags in industrial environment, the tags have to be tested and characterized at the paper mill. Before paper mill testing, the tags are tested in the laboratory environment with a suitably sized test paper reel. In this process electromagnetic modeling plays a paramount role. It is crucial in optimizing the paper reel tag parameters before moving on to laboratory and field testing. However, there are always some non-idealities when modeling results are applied in practice. Challenges also arise from the three-dimensional curved structure of the paper reel where the tag has to be embedded. In addition, the input impedance of the RFID IC is frequency dependent. Therefore, studying and developing the modeling methods for tag antennas is important.

In this paper we present the modeling based design process of a tag antenna for paper reel identification. The rest of the paper is organized as follows: Section II presents the paper reel supply chain. Section III concentrates on the requirements for the paper reel tag and Section IV presents the history of paper reel tag development. Modeling of the paper reel tag is discussed in Section V. Section VI presents the paper reel tag performance characterization results. Finally, conclusions are presented.

II. PAPER REEL SUPPLY CHAIN

The paper reel supply chain from the paper mill to the end user includes several stages. An example of a supply chain of paper reels is presented in Fig. 2 [3, 6]. The need for identification starts after the slitter machine where each reel is cut out from the parent reel and trimmed to have a specified width and web length. Nowadays, when barcode identification systems are used, the first barcode label is affixed on the other end of the reel core after the reel comes out from the slitter machine. This barcode includes the 14-caracter reel identification number. The identification numbers are given for each reel when the specific reel widths and other parameters of the reels are planned. The information about the reel – width, weight, paper quality etc. – are connected to the reel identification number and stored in the database. After the slitter machine, the reel is automatically carried forward to the packing plant using conveyor belts.

In the packing plant the reel is shielded using wear-resistant and waterproof wrapping paper. The wrapping paper is carefully folded around the reel and over the inner end disk which is a corrugated board disk that is shielding the ends of the reel. After that, the outer end disk is fixed. Nowadays when barcode systems are used in paper reel identification labels including such information as the weight of the reel, paper quality, length of the wound paper, manufacturer mill, reel width and diameter, reel identification number and the corresponding barcode are affixed on the outer surface of the reel. The label can also indicate the paper reel clamp pressure which can be used when the reel is lifted with a clamp truck. This information is also saved to a database with the barcode information and the identification number of the reel. Normally two labels are attached on the reel: one on the other end of the reel and one on the belly of the reel. After this phase the reel is carried forward to the warehouse using conveyor belts.

Paper reels are normally stored at the mill and at their end destination. In some cases on the way from the mill to the end user, the reels are stored by middlemen: stockists, export merchants and wholesalers. Warehousing should be efficient and the reels should be stored in the warehouse or in the pressroom so that each reel is readily available in the first in – first out principle so that the stock turnover can be followed. Electronic warehouse management systems are used for optimizing the rotation of the stocks and the storage plan.

In many countries paper reels are transported on roadways using trucks or on railways. Road and railway transportation is also used for carrying reels from the mills to the sea ports. Occasionally the reels are delivered directly from the mill to the ship and from the ship to the end user. At the end user location, for example inside the printing house, automated guided vehicles (AGV) carry out the feeding of paper reels for continuous printing machines.

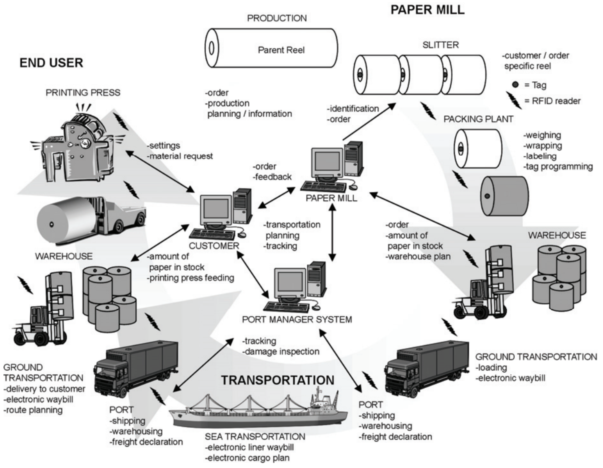

Fig. 2. Paper reel supply chain [6].

As the above explanation shows the environments in the paper reel supply chain are various and the physical properties of each of the identification points are also different. This sets a number of challenges for the use of passive UHF RFID systems in this application. For example, multipath propagation in the reflective paper mill environment may affect the identification of paper reels. In addition, to guarantee effective automatic identification, the reels should be identified with paper reel clamp-integrated readers and reader antennas. This is challenging for both the performance requirements of the paper reel tag and the functioning of clamp-integrated reader antennas.

III. REQUIREMENTS FOR THE PAPER REEL TAG

To ensure identification of paper reels throughout the supply chain and also at the end user, the safest place for the paper reel tag would be on the outside surface of the reel core under the wrapped paper. This way the tag will remain non-tampered even if the reel would be lifted with a shaft that goes through the hollow reel core. With proper antenna design, the tag can be read efficiently through the thick paper layer. The effects of paper layer – attenuation of the electromagnetic wave [7], dielectric lens effect [8], effect on the wavelength and thereby the dimensions of the tag antenna [9] – have to be taken into account in the tag antenna design process.

The most crucial requirement for RFID systems to be used in paper reel identification is the omnidirectional reading of the tag on the reel core. The structure of the paper reel and the tag placement on the reel are presented in Fig. 3. The required omnidirectional reading means, that tag has to be readable 360 degrees around it in the xy-plane, when the coordinate system is fixed as shown in Fig. 3. This requirement is based on the automation systems within the supply chain of the paper reels. Paper reels are handled with paper reel clamp trucks and where the omnidirectional reading is essential: the truck driver has no way of knowing the direction of the tag on the reel core and the driver has no time to drive around the reel to find the tag's direction [3].

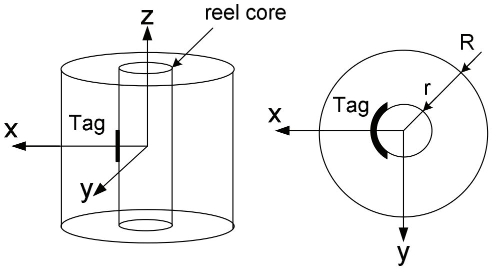

Fig. 3. Tag antenna placement on the reel core.

In addition to omnidirectional reading, there is a read range requirement for the paper reel tag. To be applicable within the supply chain, the read range of a paper reel has to be at least 1.5 m measured from the center point of the reel. Of this distance, usually 0.5-0.6 m is paper and the rest is air. Computational electromagnetic modeling plays an important role in optimization of the omnidirectional reading properties and maximizing the read range.

In addition, the paper reel tag has to be globally operable, and therefore its bandwidth should cover the frequency band used with passive UHF RFID systems (860 – 960 MHz) 0. Also, to enhance global usage the tag's microchip should support general standardization. For this research we have used EPC Gen 2 –based microchips 0.

IV. HISTORY OF PAPER REEL TAG DEVELOPMENT

The lack of suitable paper reel tag has prevented RFID systems from being used in paper industry applications. Research work for developing a suitable tag has been going on since 1980s. A suitable paper reel tag should have an application specific antenna design and small and sensitive enough microchip. Therefore, the biggest challenge in this application has been the development of an omnidirectional tag antenna which provides long enough read range with a suitable microchip.

Measurements to characterize the attenuation properties of paper reels were carried out 0 and the requirements of the UHF RFID system from the electromagnetic viewpoint were also studied 0.

Around the world several organizations have also worked on identification of paper reels with RFID systems. Technical Research Center of Finland (VTT) did research on passive bow-tie tag for paper reel identification in Palomar project 0. Also this tag antenna design was aimed for broadband operation. Ipico has published a paper reel identification system, which uses two different frequencies and coupling methods (125 kHz and 6.78 GHz) 0. Challenges in using this system arise from using two different frequencies, which requires microchips and reader units which are specifically designed for this system. In 2006 PowerID brought into market a battery assisted ForReel tag (nowadays called a PowerR tag) 0. Battery assisted tags are more expensive than purely passive tags, and the durability of the battery in the environmental conditions of the paper reel supply chain has to be taken into account. Also active RFID systems have been tested in paper reel identification. The price of active tags has been the limiting factor for their widespread use in this application. In practice, active tags can be inserted to cores which are recycled to be used again in the supply chain. In this case the core material can be for example aluminum instead of paperboard materials that are normally used.

In the early stage of the research on paper reel identification different frequency bands and coupling methods were tested. In addition to passive UHF RFID systems, passive 13.56 MHz systems based on inductive coupling were studied. At lower frequencies the electromagnetic wave propagates through attenuating material with lower losses, but the large size of the reader antenna, which was impractical in the application environment, and too short read range restricted the use of these systems in this application.

In 2002 a research project called Electronic Supply Chain Identification with Passive RFID Systems (eSCID) was started at Tampere University of Technology, Department of Electronics. One of the main research topics of this project was paper reel identification with passive UHF RFID systems. The research was started by studying the identification of broadband tags through a paper layer [9]. Promising results were achieved and the tag antennas were further developed with modeling and measurements 0, 0. The results also showed that reading a passive UHF RFID tag through a thick paper layer with sufficient read ranges is possible.

However, the biggest challenge – developing an omnidirectional tag – was still unsolved. Idea of a tag antenna which would be mounted around the reel core lead to breakthrough in development of the omnidirectional tag. The original idea was C-330 tag. The name of the tag was based on its shape: it was to cover 330 degrees of perimeter of the reel core and its mounted shape resembled a letter C. However, in the early stage of the research work the results were not as good as expected. Therefore, the tag antenna design was further developed and the C-180 tag antenna was the result of this research work. It covers 180 degrees of perimeter of the reel core. The first omnidirectional reading of a paper reel with the C-180 tag took place in 2005. This breakthrough proved that passive UHF RFID systems can be used in paper reel identification.

In 2006 a new research project, Global Paper Reel RFID (PapeRFID) was started with a wide support from Finnish paper industry. In this project, C-tag has been further developed to meet the requirements of the application, which are presented in Section III. In addition, other suitable tag antenna geometries have also been studied. For example, an array tag antenna for paper reels has been studied together with the University of Mississippi RFID research group 0. PapeRFID project was finished in April 2009. During this project, the C-tag has been tested within paper reel supply chain in various identification locations (paper mill, sea port, printing house) and with paper reel clamp-integrated reader antennas 0, 0. In addition, the industrial manufacturing of the C-tag has already begun. The C-tag meets the requirements presented in Section III.

V. MODELING

Communication between an RFID tag and the reader unit is based on modulation of backscattering of the reader's CW signal from a loaded tag antenna. This type of system resembles a radar system with the difference that the echo signal carries object's identification information. Thus the communication principle of an RFID system differs from common wireless communication where the data carrying signal is fed to a transmitting antenna and received at the other end of the link with a receiving antenna.

However, since currently in the passive UHF RFID technology the energy scavenging of the tag limits the detection range 0, for the design purposes it is sufficient to consider the tag antenna as a receiving antenna, loaded with the impedance of the IC's energy scavenging state's impedance. Consequently the design goal is to tune the antenna impedance to the complex conjugate of the of the load impedance to maximize the power delivery to the IC and thereby to achieve the maximal detection range.

Another goal for the design of the paper reel C-tag, in addition to optimal impedance matching, was to tailor the desired omnidirectional radiation pattern for the antenna when it is attached to the reel core under the paper wrapped on top of it. In general, when a tag antenna is mounted on an object, its pattern may differ significantly from its free-space pattern depending on the shape and materials of the object. Therefore co-design with the actual object is advisable. This co-design is also advantageous − and often necessary − for impedance matching of the antenna, since the nearby materials affect the antenna current and thus the impedance seen from its input terminals 0.

Most conveniently the previously discussed design goals are met by first selecting a suitable antenna geometry to produce the desired radiation pattern and then realizing the maximal power delivery to the IC by a matching network embedded in the antenna structure. If the area occupied by the matching network is small enough compared to the radiation elements of the antenna, its contribution to the radiation pattern is insignificant and the pattern adjustment and impedance tuning can be done separately.

The initial stage of the paper reel C-tag design followed the above-explained procedure. First different C-shaped geometries were tried and sufficient matching was found to be realizable with an embedded T-matching 0. After this initial stage computer simulations were conducted to predict the current distribution in the antenna structure and to characterize its radiation properties as well as to optimize its performance.

For the modeling of the C-tag we have used Ansoft High Frequency Structure Simulator (HFSS), which is a commercially available FEM-based full wave electromagnetic simulator 0. Results from different models are compared below to demonstrate the importance of an appropriate simulation model to design both, impedance matching and tailored radiation pattern for the tag.

In addition to the simulation of the antenna impedance, accurate knowledge of the load impedance, i.e. the IC's input impedance in its energy scavenging state, is crucial for the realization of the complex conjugate matching. Commonly the front-end section of an UHF RFID IC contains rectifier and voltage multiplication stages. This circuitry consists mainly of capacitors and diodes and consequently the input impedance of the chip is capacitive and depends on the frequency and input power 0. Typically the chip vendors either list this impedance at a few discrete frequency points in the operation band or provide an equivalent circuit model and related component values for a continuous impedance model. The development of the C-tag has been done with various ICs, but in this article the design of impedance matching for Alien Higgs-3 IC is studied by simulations.

In this study the antenna is mounted on the reel core and paper is wrapped around it. The reel core itself is composed of dense cardboard and the paper is standard copy paper. In reality the amount of the paper can vary through the life cycle of the reel, but for the simulations 0.3 m paper layer on top of the antenna was assumed. In our case the tag antenna is in immediate contact with only these two materials and in addition to the antenna conductor they are the only materials, which were considered in the simulations.

The electrical parameters of paper are discussed in [27]. For the paper reel C-tag design the dielectric constant of paper and the loss tangent values were set to 3 and 0.01, respectively. Dielectric constant of reel core was assumed to be 4.0 and its loss tangent was set to 0.02. Since the thickness of the conductor layer is very small compared to the reel core and paper layer, it was modeled as finite conductivity boundary with the Copper conductivity σ=58 MS/m.

The configuration studied in this paper is a 6-inch reel core with radius r ≈ 0.09, paper layer thickness 0.3 m, which corresponds to value R ≈ 0.39 m, and paper reel height H ≈ 0.53m. All these parameters are shown in Fig. 3.

Figure 4 shows simulated impedance from five different models. First model (M1), with only the planar antenna structure in vacuum, is clearly a non-realistic scenario for our study. In the second model (M2) a finite sized reel core material brick is added as substrate for the antenna. In the third model (M3) a finite sized paper brick is included in the simulation model as a superstrate for the antenna. Fourth model (M4) is the same as the third one, but in this model paper bricks are placed on both sides of the antenna. In the fifth model (M5) the reel core and the paper layer are finite-sized cylinders and the antenna structure is placed on the cylindrical reel core. This model represents the most accurate reproduction of the application's physical setting.

To simplify the design process a planar model would be preferable, since it is faster to simulate and also easier create in any simulation software.

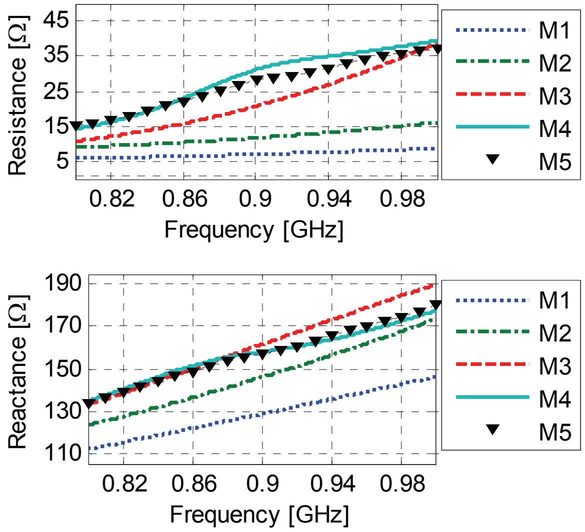

Fig. 4. Simulated antenna impedance from five different simulation setups.

Results in Fig. 4 indicate that only the planar model with reel core material (M4) and paper layers on both sides of the antenna would produce a result, which agrees reasonably well with the cylindrical model (M5).

Using a series equivalent circuit for the antenna and load impedances one can derive the power transmission coefficient 0 as

$$\tau = \frac{4R_L R_A}{\left|Z_L + Z_A\right|^2}, \tag{1}$$

where $Z_A = R_A + jX_A$ and $Z_L = R_L + jX_L$ and subscripts *A* and *L* refer to *Antenna* and *Load* respectively. This quantity is the ratio of power delivered to the load and the power available for the load and it is bounded to the interval $0<\tau\leq 1$. To predict the power transmission coefficient for the Alien Higgs-3 IC versus frequency we used the equivalent circuit model for the chip impedance provided by the manufacturer's website 0. The equivalent circuit is a parallel RC-circuit with equivalent input parallel resistance R_p = 1500 Ω and equivalent input parallel capacitance C_p = 0.85 pF. The input impedance of the chip is related to these equivalent quantities through

$$Z_{chip1}(f) = \frac{1}{j2\pi f C_p + 1/R_p}. \tag{2}$$

This model is given at −14 dBm input power for the frequency range 860 MHz to 960 MHz, but our results are plotted from 800 MHz to 1000 MHz, yet keeping in mind that the prediction may become less reliable towards lower and upper end of the studied frequency band.

During the prototype testing we found that in our case the previous chip impedance model may predict too high operation frequency. Further inspections revealed that in the prototype tag, due to an imperfect connection between the antenna and the IC strap, also additional equivalent parallel stray capacitance (C_s) may be present. Indeed, adding also this effect into the chip impedance model yielded systematically better agreement between the simulations and measurements. In this augmented model the chip impedance is given by

$$Z_{chip2}(f) = \frac{1}{j2\pi f C_s + \dfrac{1}{Z_{chip1}(f)}}. \tag{3}$$

Figure. 5 shows the chip impedances using the stray capacitance model with different estimates for the capacitance value and Figs. 6 and 7 show the corresponding power transmission coefficients for different simulation schemes and stray capacitance values C_s = 0 and C_s = 0.2 pF respectively.

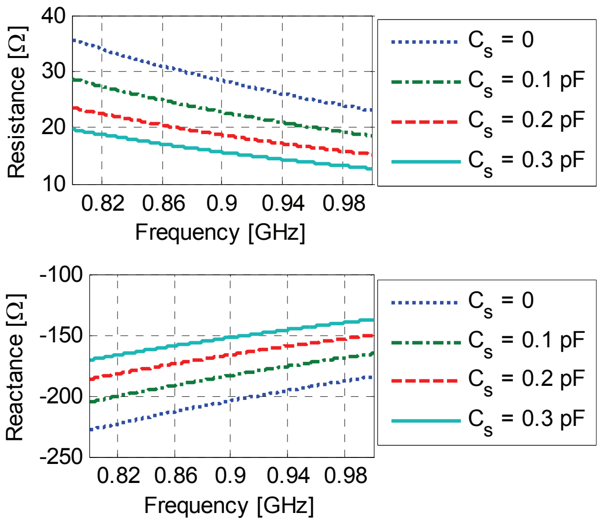

Fig. 5. The effect of the stray capacitance to the input impedance of the IC chip.

Results in Figs. 5, 6, and 7 indicate that only the two most simplistic simulation setups; planar vacuum model and the planar reel core model, predict notably different power delivery compared to the other three setups, which all give quite similar predictions. Another observation is that the impedance model for the IC chip is sensitive for additional parasitic effects related to the chip attachment; in the presented example the augmented model with C_s = 0.2 pF shows already 50 MHz frequency shift in the operation frequency of the tag compared to the nominal model.

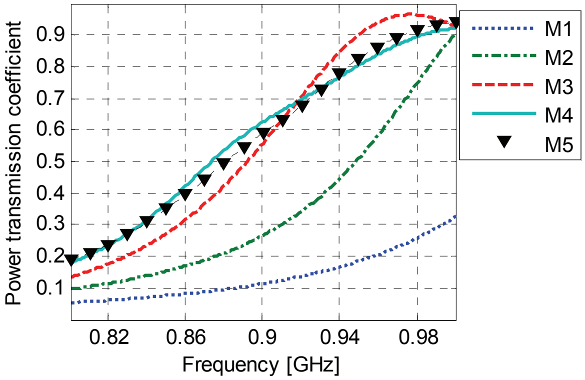

Fig. 6. Power transmission coefficient with an ideal antenna-chip connection (C_s=0).

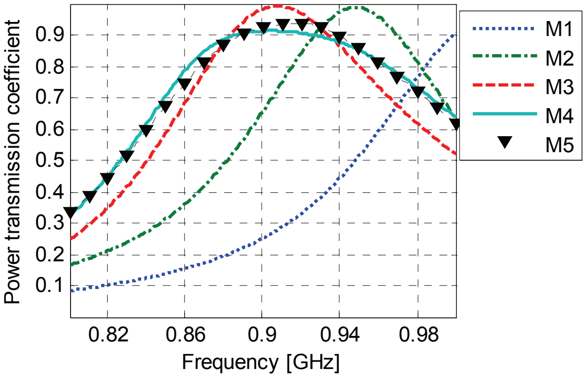

Fig. 7. Power transmission coefficient with stray capacitance value C_s=0.2 pF.

Figure 8 shows the simulated directivity pattern at 866 MHz with different simulation setups in the xy-plane as shown in the Fig. 3. 866 MHz frequency was chosen because it is the UHF RFID band center frequency in Europe and therefore suitable for comparison. Results are plotted using standard spherical coordinates, where 0°

corresponds to the direction of the positive x-axis and the angle 90° corresponds to the direction of the positive y-axis. Results in Fig. 8 show more variation between the different simulations setups than the simulated antenna impedances.

The two most simplistic setups; planar vacuum model and the planar reel core model yield an almost omnidirectional pattern cut, which is similar to a dipole H-plane. Planar simulation model with antenna on the reel core material slab and paper layer on top of it (red curve) has distinct maxima near +/− 30 degrees and in the region 75 degrees to 285 the pattern oscillates between 0 and −5 dBi. The blue curve is obtained from a similar model as the red one, but in this model the paper layer is on both sides of the tag. This simulation setup does not predict the two maxima like the previously discussed model and the obtained directivities remain between 0 and −5 dBi for almost all observation angles. This result is already quite close to the most realistic scenario with the conformal tag model (black curve), but it can be seen that the result from the conformal model is smoother and predicts greater directivities especially in the forward direction. Therefore, when both the radiation pattern and the impedance matching are considered, the conformal simulation model seems to be a better choice than the other more simplistic models with planar geometry.

To provide an overview of the simulated radiation characteristics of the C-tag in a 6-inch reel core with 30 cm paper layer on the reel, the simulated directivity at four directions around the reel from the conformal model are plotted in the Fig. 9 at three different frequencies in the horizontal plane cut indicated in the Fig. 3. The selected frequencies in Fig. 9 are UHF RFID band center frequencies in Europe, North America and Japan, respectively. The simulated radiation efficiency at all these frequencies is 85%.

Directivity patterns in Figs. 8 and 9 suggest that the readability of the tag around the paper reel remains similar through the global UHF RFID frequencies. At all three frequencies of interest, there seems to be an asymmetry in the patterns, so that more radiation is directed to angles over 180 deg. This is explained by the feed network, which results to a slightly asymmetric current distribution shown in the Fig. 10. According to this result more current concentrates on the antenna structure on the feed point side than on the opposite side. Symmetric current distribution could be attained by introducing an asymmetry to the radiating structure on the right hand side of the split plane, or by using a symmetric matching structure instead of the T-matching network.

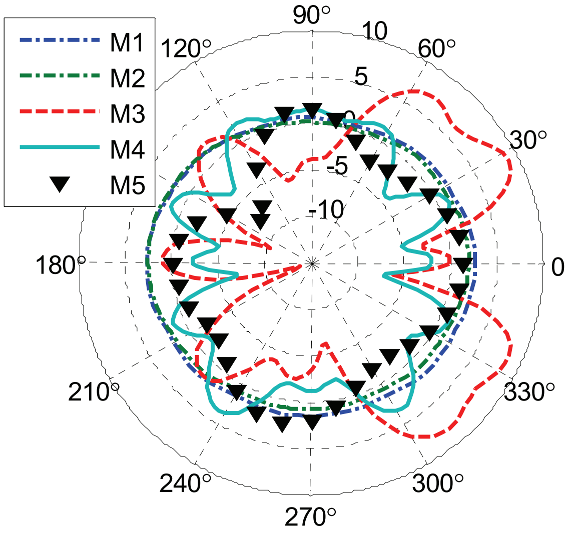

Fig. 8. Directivity [dBi] of the paper reel C-tag at 866 MHz in the xy-plane (as in Fig. 3).

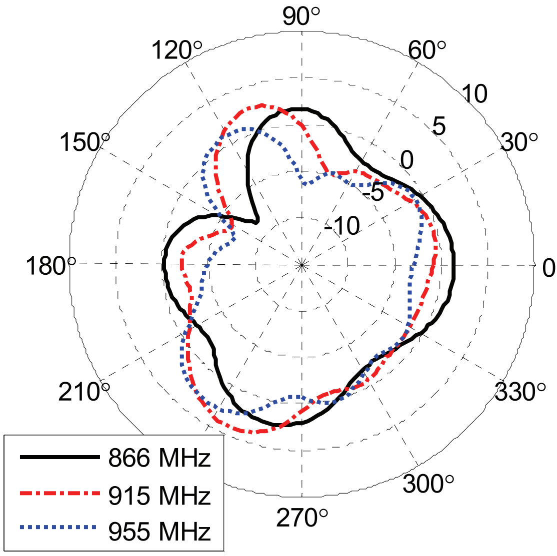

Fig. 9. Directivity [dBi] of the paper reel C-tag, from model M5 in the xy-plane (as in Fig. 3) at three different frequencies.

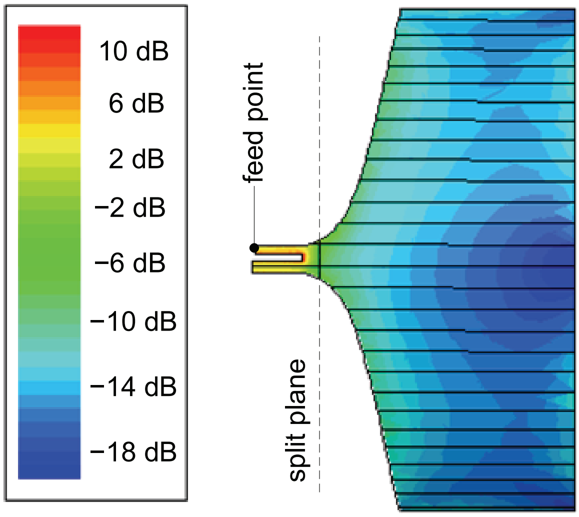

Fig. 10. Maximum surface current density distribution in decibels, normalized to the maximum value on the right hand side of the split plane.

VI. CONCLUSIONS

Requirements, design principles and modeling methods for an RFID tag antenna for industrial paper reel identification were discussed and the history of the C-tag antenna development was summarized. Electromagnetic modeling plays a key-role in the development of tag antennas for challenging objects, such as paper reels. The modeling results from the presented simulation case clearly support a careful co-design with the actual object, in this case mounting the antenna on a curved surface. Mounting and nearby materials affect the radiation pattern of the tag antenna. In addition, the realization of the chip-antenna connection can not be neglected in the design of the impedance matching.

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