Passive UHF RFID in Paper Industry: Challenges, Benefits and the Application Environment

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Abstract—Radio frequency identification (RFID) systems for the paper industry is an emerging research topic due to the need for an automated identification system for the paper industry which would carry on the identification codes of paper and board reels throughout their life cycle. This paper discusses the application of passive ultra-high frequency (UHF) RFID systems to the paper industry. Challenges, benefits, and the application environment of using passive UHF RFID systems in the paper industry are presented and discussed. In addition, the identification locations within the paper reel supply chain and the effects of RFID systems to supply chain visibility are presented and discussed. In addition, test results of using passive UHF RFID systems in the paper industry environment are presented.

Note to Practitioners—An automated identification system, which would carry on the identification code of a specified paper or board reel throughout its life cycle, is needed in the paper industry. Nowadays when barcode identification systems are used the identity of the reels disappear when the wrapping of the reel and at the same time the barcode are removed. The RFID tag, however, would be attached to the paper reel core and thereby the identification code of the reel is restored throughout its life cycle. RFID systems would benefit the paper industry by enhancing the supply chain visibility and providing a more automated identification system than barcode identification. In the future, paper reels will be identified with clamp truck-integrated reader units which, on the other hand, enables adding more real-time information about the locations of the paper reels to information databases but also sets challenges for paper reel tag performance and integration of RFID reader units and reader antennas to paper handling machinery. This paper concentrates on passive UHF RFID systems and their application to the paper industry. Challenges and benefits of RFID systems in the specific application environment of the paper industry are presented and discussed.

Index Terms—Paper industry, radio frequency identification (RFID), tag antenna designs.

I. INTRODUCTION

The paper industry needs an automated identification system which would carry on the identification code of a specified reel throughout the whole life cycle and supply chain of paper and board 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, with radio frequency identification (RFID) systems, it would be possible to identify the individual reels from cradle to grave. In this case, 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 or board mill to the end user, for example, in printing companies [1], [2]. The outside surface of the core under the wrapped paper is the best place for the tag because some reel handling machines have a shaft that goes through the core. In this case, a tag that is placed on the inside surface of the reel core would very likely be damaged. RFID systems would benefit the 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 and the supply chain visibility [1]–[3].

The application of RFID in paper industry has been under research and development for the past decade. Pilot tests have been carried out to study the operability of different types of RFID systems in paper reel identification. Considering the high frequency (HF) RFID systems operating at 13.56 MHz, the problems have been achieving sufficient read range and the integration of large HF RFID reader antennas to paper reel handling machinery, such as clamp trucks. Also, the use of semi-passive UHF RFID systems with a battery which is supporting the backscattering process have been proposed to paper reel identification due to increased read range [4]. Compared with passive systems, semi-passive systems are more expensive and the durability of the tag’s battery, for example, in very cold environments is also an issue to consider. This paper concentrates on analyzing the use of passive UHF RFID systems in paper reel identification. Recently, promising results of identifying paper and board reels with passive ultra-high frequency (UHF) RFID technology have been achieved [2],
After these studies, the development of passive UHF RFID systems has been carried forward. This paper presents the most recent results of the research work concentrating on tag antenna development for paper and board reels and performance testing of passive UHF RFID systems in the paper industry environment.

The benefits of this technology are sufficient read range of the paper reels from desired orientations, cost-effective microchips, possibilities for different tag antenna variations, relatively compact reader antenna sizes for clamp-truck integrated readers, and the possibility to use globally standardized RFID technology due to EPC Gen2 specification [7].

Before passive UHF RFID systems can efficiently be applied to paper reel identification, a number of challenges have to be confronted and solved. The application environment within the supply chain of paper reels is very complicated, and paper and board reels are complex objects with several boundaries and various material properties.

The placement of the tag between the core and the paper or board sets challenges for passive UHF RFID. The lack of a well-functioning, application specific tag antennas for identification of paper and board reels has been the major issue obstructing the application of RFID systems in the paper industry. Tags that carry on the identification code consist of an antenna and a microchip. 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 transmitted by the reader. The communication in passive UHF RFID systems is based on backscattering of modulated electromagnetic wave: reader transmits energy, commands and data to tag which then responds by backscattering its identification data that is modulated to the carrier wave back to the reader [8], [9].

In addition to tag antenna development, many issues have to be addressed: the identification locations of reels in the supply chain have to be planned, the data content of the tag’s microchip has to be defined, the RFID systems have to be integrated into the existing data management systems and clamp-truck integrated reader units and reader antennas have to be developed.

This paper presents and analyses the challenges, benefits, and the application environment of the use of passive UHF RFID systems in the paper industry. The paper reel supply chain is presented and the effects of RFID on the paper reel supply chain management and visibility are discussed. The application of passive UHF RFID in the paper industry is also discussed and analyzed with performance testing in the paper industry environment. This paper addresses the major challenges of applying passive UHF RFID in the paper industry, which are development of an omnidirectional tag antenna and integrating the reader units and reader antennas to paper handling machinery.

II. PAPER REEL SUPPLY CHAIN

This section describes the structure of the basic supply chain of paper reels and clarifies the role of barcode identification systems that are in use in paper reel identification at the moment. 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. 1 [10]. 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. The barcode label affixed to the reel core is presented in Fig. 2. This barcode includes the 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. Fig. 3 presents the paper reel label.

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 customer. In seaports, specific mafi trailers are used to transfer reels to and from the ship. Planned loading reduces costs and delays in delivery.

Inside the printing house, automated guided vehicles (AGVs) carry out the feeding of paper reels for continuous printing machines. Fig. 4 presents an AGV carrying a paper reel.

By means of a call key system, the printing machine operator requests new paper reels on demand. From this electronic request, the control system generates a transport order. The AGV carries the paper reel of the desired paper quality from the stock where the reels are prepared and stored and takes it to the printing machine that is requesting it.

## III. APPLICATION OF PASSIVE UHF RFID IN THE PAPER INDUSTRY

Many issues have to be considered when passive UHF RFID systems are planned to be applied in the paper industry. This section concentrates on analyzing the attachment of the tag on the reel core, the possible identification locations of the reels, the data content of the tag’s microchip, and the desired read range and reading directions of the reels.

### A. Attachment of the Tag on the Reel Core

Reel cores are usually made of fiberboard, which can contain recycled and new material. The thickness of the fiberboard layer

![Fig. 2. Bar code label affixed to the end of the paper reel core.](image1)

![Fig. 3. Paper reel label.](image2)

![Fig. 4. The AGV carrying a paper reel.](image3)
varies between 10–15 mm. For example, a 15-mm thick fiberboard layer contains 32 individual layers of 0.5–0.6-mm thick fiberboard. These fiberboard layers are glued tightly together. The inner diameter of reel core can be 3 inches (76.2 mm) or 6 inches (152.4 mm). In addition, 9 inch (228.6 mm) and 12 inch (304.8 mm) reel cores are used, for example, in board mills. The widths of the full reel core rods depend on the widths of the slitter machines used in the individual paper mills. At the paper mill, the reel core rod is cut into cores of individual reels according to the customer order.

The tag should be attached to the individual reel core after it has been cut to its final width. This is because the tag should be placed at the middle of the width of the reel core. In addition, the tag should be affixed tightly to the core because the tag has to endure the rolling process of paper at the slitter machine. At this point, when the tag has been attached to the reel core, the reel identification number can be programmed to the tag microchip’s memory.

As noted above, nowadays reel cores are cut to their final width at the paper mill. In the future, when the RFID tags have to be placed on the reel cores, precutting the reel cores and attaching the tags before the cores are shipped to the paper mill is one possible new business process.

B. Identification Locations of Paper Reels

This section presents a description of possible paper reel identification locations within the supply chain. The paper reel supply chain is presented in Fig. 1.

The first identification location for the reel would be right after the slitter machine. At this point, the reel has been issued an identification number. The identification would take place when the reels are moved towards the packing plant on a conveyor belt. In this paper, Section V-A presents identification test results of reels moving on a conveyor belt.

The second time for reel identification would be the arrival to the packing plant. At this point, the reel identification would indicate which reels have arrived for packaging. Third, the reels should be identified when leaving the packing plant.

After leaving the packing plant, the reels are transported to a warehouse using, for example, road transport. In the next stage, the reels are moved to the warehouse with, for example, a clamp truck. At this point, the reels should be identified with a clamp truck-integrated reader unit. When the reels are identified with a clamp truck-integrated reader unit, information, for example, about the clamp truck lifting pressure and the location of the reel in the warehouse could be saved to the database. In this paper, Section V-B presents identification test results of paper reels using a clamp-truck integrated reader unit.

From the warehouse, the reels are moved to transportation. The paper reels are transported by boat, by road truck, or using railways. Nevertheless, the reels have to be identified when moved from the warehouse to the specific transportation vehicle to ensure that the loading is carried out according to the cargo plan. Section V-C in this paper presents identification test results of paper reels placed on a moving maft trailer which transports the reels to the sea ship.

Arrival of the reels to the end user is the next identification location in this model. The reels are moved from the transportation vehicle to the end user warehouse using, for example, clamp trucks. From the end user warehouse, the reels are taken into use. Moving the reels, for example, in the printing house can be carried out with AGVs that should thereby have an onboard reader unit. When some special paper qualities are used in small printing batches, the reel can be moved back to the warehouse. At this point, RFID gives a special feature compared to barcodes: the reel with an RFID tag maintains its identity and it can be identified when the reel is again taken into use. Reels with barcodes lose their identity when the wrapping is removed at the point of using the reel for the first time. After this it is very challenging to identify the reels seamlessly.

All this identification information would be stored to a database which authorized users, such as the manufacturer and the client, would have access to. These kinds of databases already exist and thereby the integration of RFID systems to the paper industry should be relatively straightforward from the viewpoint of information systems. RFID would enable more visible, efficient and automated paper reel supply chain by enabling automated reel identification with clamp truck-integrated reader units and by restoring the reel identity throughout the supply chain from the paper mill to the end user.

C. Requirements for the Read Range With Passive UHF RFID Systems

Due to the requirement of identification of the reels with a clamp truck-integrated reader unit, the reels have to be identified omnidirectionally, i.e., 360° around the reel in horizontal plane. When reels are identified with a clamp truck-integrated RFID reader unit, the reel is clamped from arbitrary direction, and despite of that fact the reel has to be identified reliably. In addition, reading from any direction is a requirement also when the reels are identified at any other location in the paper reel supply chain, for example, on a conveyor belt. In practice, omnidirectional reading means that there is no need to turn the reel for desired identification orientation. The concept of omnidirectional reading is presented in Fig. 5.

Also, certain requirements are set for the read range of paper reels. In the following specification, the read range is measured from the center point of the reel, and thereby the actual read range includes the paper reel radius and the distance in free air from the paper reel surface. Read range from the center of the reel should be at least 1500 mm despite the radius of the reel and...
paper or board quality. In this specification, the maximum thickness for paper or board layer is 900 mm. The remaining reading distance will be an in-air distance measured from the paper or board layer surface. However, currently the maximum diameter for board reels is 2100 mm. In this case, the sufficient read range measured from the board layer surface is 300–400 mm.

The read ranges presented above are sufficient for reel identification because much longer read ranges would not give significant benefits to the supply chain management. In identification of paper and board reels, it is important to know which reel is identified in the reader’s interrogation zone. Read ranges of several meters might disturb the identification process because generally only one reel at a time is needed to be identified. In addition, when reels are identified with a clamp truck-integrated reader unit the reader antenna will be brought very close to the identified reel.

D. The Information Content of the Microchip

Depending on the memory size and type of the RFID microchip, different amounts of data can be written and stored on the microchip. In its most minimalist form, the microchip memory contains the identification code, which in this case is usually the 14-character reel identification number. Also, for example, the electronic product code (EPC) in its basic form contains 96 bits. On the contrary, some microchips can contain for example 2000 bits user-programmable information [11].

In the case of paper reel identification, the preferable information content of the microchip would be only the reel identification number. All the other real-time information, for example, about the handling locations of the reel would be stored to the database. Due to the attenuating properties of paper, the probability for bit error is high. If the bit-error rate is, for example $10^{-2}$, which means that every 100th bit is lost, the 96 bit identification code is read quite reliably despite the challenging environment. However, if a 2000 bit identification code has to be read through paper, multiple queries are needed to interrogate the whole identification data of the tag. This increases the reading time and makes the identification more unreliable [11].

It should also be noted that though tags can be read through paper, writing information to tag’s memory correspondingly through paper is even a more challenging task. This also speaks for using 96 bit read-only tags in paper reels and storing the further information to a suitable database.

IV. CHALLENGES IN APPLYING PASSIVE UHF RFID IN THE PAPER INDUSTRY

The paper industry is a very challenging application environment for passive UHF RFID systems. This section presents two of these challenges: the challenges in paper reel tag antenna design and clamp truck-integrated reader unit and reader antenna development.

A. Designing an Omnidirectional Tag Antenna

Due to the placement of the tag, the tag’s antenna has to be designed to operate through paper or board. When an electromagnetic wave propagates through paper or board, its wavelength, speed and amplitude decrease. The decreased wavelength is defined as the ratio of the free-space wavelength at the specified frequency and the square root of the dielectric constant of paper, and it affects the electrical dimensions of the tag antenna inside the reel [2], [11], [12]. 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.

In addition to the ability to read the tag through paper or board, the biggest challenge has been developing a tag antenna that would be readable omnidirectionally. This means that the vertically orientated reel can be identified horizontally 360° around it. The concept of omnidirectional reading is explained in Fig. 5. This feature is crucial, for example, in clamp truck handling of the reels.

At the moment there is a variety of commercial passive UHF RFID tags available. We have previously tested these usually dipole-type tags in paper reel identification by attaching the tag on the reel core after which the paper was wrapped around it [2]. With standardized UHF RFID equipment, it is possible to identify commercial tags through an industrial paper reel on some directions but omnidirectional reading around the reel is not possible with these commercial tags [2]. Commercial tags are usually based on small dipole antennas and thereby their radiation properties, for example radiation pattern and radar cross section (RCS) are not suitable for omnidirectional reading through a thick layer of attenuating material. The ability to identify the tag from any direction around the reel is indispensable in clamp truck handling: the truck driver has to be able to grab the reel with the truck clamps from any direction, and the reel must be identified automatically with a clamp truck-integrated reader unit. This way the time stamps of handling the reel in different locations can be saved to the database and tracked.

Achieving optimal performance of tags in paper industry applications requires careful designing of tag antennas taking into account the effects of paper and board on the antenna performance. Board is defined as a heavyweight sheet generally made from waste paper and has a thickness of more than 0.15 mm. Whereas paper contains one main material layer, board typically has several layers. The dielectric properties of paper and board have a paramount effect on designing tag antennas for paper reel identification. One of the most important parameters is permittivity ($\varepsilon_r$). Permittivity describes the polarizability of the material in an external electric field. Since the values of $\varepsilon$ are in the order of $10^{-11}$ F/m, it is more practical to use the dielectric constant ($\varepsilon_r$), which is the ratio of the permittivity of the material and the permittivity of vacuum ($\varepsilon_0$)

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}.$$  

(1)

The dielectric constant of paper varies typically from 2 to 4 depending on density, filler content, fiber furnish, etc. Also, moisture content has some effect on the dielectric constant of paper. Dielectric constant is also frequency dependent decreasing with frequency [2], [12], [13].

The dielectric constant of paper increases with increasing density and the behavior follows with reasonable accuracy the Clausius–Mossotti relation:

$$\frac{\varepsilon_r' - 1}{\varepsilon_r' + 2} \propto \rho_d$$  

(2)

where $\varepsilon_r'$ is the real part of the complex dielectric constant and $\rho_d$ is the density of paper. Fillers, for example, $\text{CO}_3$ and
kaolin, increase the density of paper, and also the dielectric constant of fillers is usually higher than the dielectric constant of wood fibers. 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 [13].

Dielectric properties of paper are also affected by the moisture in paper. Typically, the moisture content of paper is 3%–7%. When board reels come out of the slitter machine, their moisture content can be up to 10%. However, the change in the moisture content does not significantly change the dielectric constant of paper itself, although the dielectric constant of water is nearly 80. This high dielectric constant is due to the permanent dipole moment of water molecules. However, in paper, water molecules are attached to cellulose chains, and therefore they cannot rotate freely. A water molecule attached to cellulose chain is free to orientate itself parallel to the electric field only if the field is parallel to the orientation of the cellulose chain. Since the chain orientations in paper are random, only a small fraction of the water molecules have perfect alignment with the electric field. Therefore, the effect of water on the dielectric constant of paper is smaller than would be expected if the water molecules were free. However, the increase in moisture content increases the dielectric losses of paper [2], [13].

The dielectric properties of paper have a direct influence on the wavelength of the electromagnetic wave propagating through paper and therefore on the electrical dimensions of the tag antenna itself. The tag antenna is placed on the reel core between the reel and the paper. The decrease in the wavelength inside the paper layer wrapped around the core can be defined with

$$\lambda = \frac{\lambda_0}{\sqrt{\varepsilon_r}}$$  \hspace{1cm} (3)

where $\lambda$ is wavelength in paper, $\lambda_0$ is free-space wavelength and $\varepsilon_r$ is the dielectric constant of paper [2], [11], [12]. Since the dimensions of tag antennas at UHF frequencies are proportional to the wavelength of the RFID system frequency, this decreased wavelength has to be considered when the tag antenna is designed to operate through paper.

Different reel and reel core diameters also cause challenges for paper reel identification. Generally, reel diameters vary between 400–1800 mm. Reel core inner diameters are either 3, 6, 9, or 12 inches. The tag antenna design should be functioning with all paper and board qualities. However, the dimensions of the tag antenna can be varied according to the reel core diameter. The tag should be placed at the middle of the reel width. This way, the location of the tag inside the reel is known and this arrangement also encourages the clamp truck drivers to handle the reels in the right way. The reels should always be lifted by grabbing the reel from the middle of the reel width to prevent damages.

In addition, the worldwide UHF RFID bandwidth covers frequencies from 865 to 960 MHz. Thereby, the tag has to be functioning within this bandwidth.

1) Omnidirectional Tag Antenna Designs for Paper Reels:

The lack of a well-functioning, omnidirectional tag antenna for paper reels is a major issue impeding the application of RFID systems to paper industry. Therefore, the suitable tag antenna design has to be developed first to enable the identification of the reels according to the specified read range requirements.

As examples of omnidirectional tag antenna designs for paper reels that are under research and development are the C-tag antenna [2], [5] and the array tag antenna design [6]. The geometry of the C-tag flat and mounted around the reel core is presented in Fig. 6. 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 board. The larger area of the C-tag increases the RCS of the antenna design, and thereby increases the area for harvesting energy to the microchip and backscattering the identification data back to the reader [14]. In other words, the larger surface area of the C-tag compared with the commercial tags and its mounting around the reel core enables the omnidirectional reading around the paper reel [2]. The first version of the C-tag design is presented in [2]. The geometry of the C-tag has then been further developed and the results of the following version have been presented in [5]. This paper presents the most recent C-tag geometry with reading performance results. The presented C-tag design has enough reading performance for application testing in paper industry environment.

The geometry of the three-element array tag design is presented in Figs. 7 and 8. Fig. 7 presents the array tag design flat. The antenna design has one antenna element (the middlemost in Fig. 7) to which the microchip is connected and two reflector elements to enable the omnidirectional reading. Length of the bow-tie elements was 100 mm.

2) Read Range Measurements:

To verify the functioning of the C-tag antenna design and the three-element array design in practice and to study their parameters, measurements at the paper mill were carried out. The purpose of the measurements was to study the read range of the C-tag and the three-element array tag when they were placed on the core of the paper reel.
under the paper layer. The paper quality used in the measurements of the C-tag was coated offset printing paper and the diameter of the paper reel was 960 mm. The paper quality used in the measurements of the three-element array was newsprint paper and the reel diameter was 1000 mm.

Read ranges of the C-tag and three-element array were measured with 915 MHz FCC compatible Gen 2 reader unit and linearly polarized reader antennas from eight directions, as presented in Fig. 9. Read ranges of the C-tag were measured also with 866 MHz ETSI compatible reader unit to compare the read ranges with both of the frequency bands. The gain of the reader antennas was 6 dBi. Figs. 10–12 present the measured omnidirectional read ranges. The read ranges are measured from the center point of the reel, i.e., the presented read range includes the reel radius (for example, 0.48 m) and the free air distance from the paper reel surface. These read ranges can be compared to the read range requirement presented in Section III-C. The reel core outer diameter was 105 mm (3 inch core). S in Figs. 10–12 indicates the direction of the IC chip, which is equivalent to direction 1 in Fig. 9.

The results show that both the C-tag antenna and the three-element array design can be read omnidirectionally through an industrial paper reel with standardized RFID equipment. The performance of the C-tag antenna design is confirmed within both ETSI and FCC frequency bands and regulations. With the tested reel diameter, C-tag antenna complies with reading requirements presented in Section III-C.

3) RFID Signal Analysis: Read range measurements presented in the previous section shows the practical performance
of the tag antenna designs. However, for research work in further developing the tag antenna designs, it is important to gain knowledge about the identification process in the signal level. Threshold power level and backscattered signal strength are important characterization parameters of tag functioning.

Very often the limiting factor for tag read range is the delivery of power to the IC chip of the tag. The transmitted power by the reader is determined in the communication regulations, and thereby the power delivery to the IC chip at a given distance is determined by the tag antenna design. The IC chip requires a certain amount of power to operate, and the tag antenna design and its matching structures determine how efficiently the power is delivered to the IC chip. In addition, the materials in the vicinity of the tag affect the properties of the antenna and the IC chip. We studied the threshold power level, which means the minimum transmission power required to activate the tag at a specified distance, of the C-tag inside the industrial paper reel. The threshold power levels were measured omnidirectionally at eight measurement directions, which are presented in Fig. 9.

However, the operating range and the reading reliability of the tag depends also on the backscattered signal strength which is detected at the receiver of the reader. The minimum signal strength which the reader can reliably detect and decode is usually presented as the sensitivity of the reader (a power level in dBm). Typically, the sensitivity of a commercial reader unit is around −70 to −90 dBm. A typical method for measuring the backscattered signal from the tag is using a signal source attached to a transmitting antenna to send a query command to the tag. The strength of the backscattered signal is then measured with a vector signal analyzer. The measurement can be carried out with different transmission frequencies and power levels for further tag characterization.

In the threshold power and backscattered signal measurements conducted for this paper, we used Tagformance measurement system [15]. Fig. 13 presents the measurement setup at paper mill. The gain of the transmitting and receiving antennas was 9 dBi and their polarization was linear. The −10 dB S11 bandwidth of the antennas was from 824 to 896 MHz. In this case, the measurement distance from the tag was 0.60 m, of which 0.44 m was paper and 0.16 m was air.

Figs. 14 and 15 present the (i) threshold power level and (ii) backscattered signal strength at threshold power level measured at 866 and 915 MHz. The results show that the achieved read range is affected by the two factors, and also the environmental conditions, such as reflections and multipath propagation which take place at the practical paper mill reading environment. Generally, the threshold power levels and the backscattering signal strength is feasible, taking into account that the measurements have been carried out through the attenuating paper layer.

B. Integrating Reader Units and Reader Antennas to Paper Handling Machinery

Seamless integration of reader units and reader antennas to paper handling machinery is crucial for reliable and efficient identification of paper reels. When paper reels are moving on a conveyor belt inside the paper mill, one or more reader antennas can be used in identification in a gate configuration. However, integrating readers and reader antennas to clamp trucks is more challenging.

As noted earlier, in clamp truck handling the tag has to be readable from all the directions horizontally around the paper reel when the reel is in vertical orientation. Omnidirectional
reading ability eliminates the direction dependence of reading the tag. The reel can then be crabbed from any direction with the truck clamps and the tag is then read with the integrated clamp truck RFID reader unit [2], [11]. In addition, when the tag can be read omnidirectionally, only one reader antenna instead of two or more reader antennas in a gate configuration can be used at all identification locations, for example, in the paper mill.

There are three possibilities to integrate an RFID system to the clamp trucks. One can use existing reader units, which are relatively compact, and connect the reader antenna to the reader unit with coax cabling. Identification information would be transferred to the user terminal inside the truck with IO-cabling. However, since the clamp trucks are working in harsh environments and, for example, a significant amount of shaking occurs when the truck is moving, general-purpose RFID readers and the coax cabling is not a durable solution for this application.

Nowadays, there are reader units that are specifically designed for forklift use [16]. In many of these readers, the reader antenna and the RF front end of the reader are integrated together and the identification information is transferred to the user terminal inside the truck with IO-cabling or wireless connection. This would be a preferable solution also for paper reel clamp trucks.

In addition, in the future, the clamp truck integrated reader unit could be totally wireless: the identification information would be transferred wirelessly using, for example, Bluetooth and the reader unit would have a rechargeable power source. The problem in this solution is the power source of the reader. There should be found an ample time in the process to recharge the batteries. Thereby, research should also be carried out to study the possibilities of energy scavenging from the kinetic energy of the clamp truck [17].

Since the reader antenna would be affixed to the paper reel clamps, special challenges arise also for the development of the reader antenna. Beam steering with antenna arrays [18] offer a possibility to search for the tag antennas in paper or board reels when the reader unit is integrated into a clamp truck. As an improvement to beam steering, perpendicular beam scanning that is presented in Fig. 16 can be used in clamp truck-integrated readers to minimize the signal path from reader to tag and vice versa. Perpendicular beam scanning also gives aid in avoiding the reflections on the air-paper boundary. In addition, relatively narrow beam reader antennas should be used in perpendicular beam scanning to minimize the effect of noise originating from the surrounding wireless communication systems [11].

V. PERFORMANCE TESTING IN THE APPLICATION ENVIRONMENT

A. Conveyor Belt Reading Tests

The purpose of the conveyor belt reading testing was to verify identification of moving reels on the conveyor belt at paper mill. Identification took place right after the slitter machine. Figs. 17 and 18 present the measurement environment and measurement set up. Alien Technology’s ETSI and FCC compliant reader units with linearly polarized antennas (6 dBi gain) were used in the testing. The distance between the reel’s outer surface and the reader antenna was 0.30 m. The reader antennas were placed on only one side of the conveyor belt to verify the omnidirectional reading. Also, multiple reader antennas in gate configuration on both sides of the conveyor belt can be used in this application.
TABLE I
READING RESULTS OF THE CONVEYOR BELT TESTING

<table>
<thead>
<tr>
<th>Reel number (XXXX)</th>
<th>Tag ID code (YYYY)</th>
<th>Identification (ETSI) (+/-)</th>
<th>Identification (FCC) (+/-)</th>
<th>Tag orientation relative to the reader antenna</th>
</tr>
</thead>
<tbody>
<tr>
<td>4310</td>
<td>7760</td>
<td>+</td>
<td>+</td>
<td>↓</td>
</tr>
<tr>
<td>4308</td>
<td>7761</td>
<td>+</td>
<td>+</td>
<td>←</td>
</tr>
<tr>
<td>4306</td>
<td>7766</td>
<td>+</td>
<td>+</td>
<td>→</td>
</tr>
<tr>
<td>4501</td>
<td>7769</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>4410</td>
<td>7800</td>
<td>+</td>
<td>+</td>
<td>←</td>
</tr>
<tr>
<td>4408</td>
<td>7806</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>4406</td>
<td>7804</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>4401</td>
<td>7794</td>
<td>+</td>
<td>+</td>
<td>↓</td>
</tr>
<tr>
<td>2110</td>
<td>7778</td>
<td>+</td>
<td>+</td>
<td>↓</td>
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<td>2108</td>
<td>7763</td>
<td>+</td>
<td>+</td>
<td>←</td>
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<td>2106</td>
<td>7795</td>
<td>+</td>
<td>+</td>
<td>↓</td>
</tr>
<tr>
<td>2101</td>
<td>7772</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>2210</td>
<td>7733</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>2208</td>
<td>7743</td>
<td>+</td>
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<td>↑</td>
</tr>
<tr>
<td>2206</td>
<td>7735</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>2201</td>
<td>7744</td>
<td>+</td>
<td>+</td>
<td>←</td>
</tr>
<tr>
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<td>7737</td>
<td>+</td>
<td>+</td>
<td>←</td>
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<tr>
<td>2301</td>
<td>7745</td>
<td>+</td>
<td>+</td>
<td>↑</td>
</tr>
<tr>
<td>2306</td>
<td>7740</td>
<td>+</td>
<td>+</td>
<td>←</td>
</tr>
<tr>
<td>2308</td>
<td>7734</td>
<td>+</td>
<td>+</td>
<td>←</td>
</tr>
</tbody>
</table>

Fig. 18. Reels passing the reader unit.

Twenty reels with the newest version of C-tag were used in the testing. Fig. 6 presents the C-tag design. The width of the reels was 880 mm and the diameter was 960 mm. Paper quality was offset printing paper. All 20 tags had different EPC codes which were then linked with the reel number of each reel. The tag microchip used in the testing was Alien Technology’s Higgs Gen 2 microchip.

Table I presents the results of the conveyor belt testing. All the reels were identified with both of the reader units. As presented in Table I, the orientation of the tag’s microchip relative to the reader antenna was also noted. The reader antenna was on the left side of the arrow in Table I (i.e., this sign ← points towards the reader antenna). The results show that at 0.30 m reading distance the orientation of the tag’s microchip does not have an effect on the reading reliability.

B. Reading Tests on the Clamp Truck

The purpose of the clamp truck testing was to verify the identification of paper reels grabbed by clamp truck. In this testing existing commercial reader units and antennas were used. The reader unit was placed in the cabin of the truck. The measurements were performed with three different kinds of reader antennas, with six paper reels. Diameter of all reels was 1250 mm. Widths of the reels were 1440 mm (reel 1), 1290 mm (reel 2), 856 mm (reel 3), 1440 mm (reel 4), 1290 mm (reel 5), and 856 mm (reel 6). Paper quality was coated offset printing paper. All reels were grabbed once with the clamp truck, and the identification with all antennas was then verified separately. Reel number 6 was stacked on top of reel number 3, and they were grabbed together from the center point of the stack. Reel number 2 was grabbed from all the eight different directions (directions seen in Fig. 9) and the identification was again verified for all antennas separately. Reels were located on a mafi trailer, and their locations and tag directions can be seen in Fig. 19.

The grabbing point of the paper reel should always be in the middle of the reel width, where the grip is most stable and durable. Then, the identification process is stable and the results are reliable. In these tests, the grab was always made in the middle of the reel, to get the reliable results.

The antennas were attached to the clamp truck forks, as presented in Fig. 20. Antenna 1 was placed in the center, above the clamps, and antennas 2 and 3 were placed between the clamps on each side. Antenna 1 was Intermec IA39B circularly polarized antenna, with 10.5 dBi gain and rugged fiberglass radome. Antenna 2 was smaller Intermec IA33D circularly polarized antenna with 6.0 dBi gain and metal cell specifically designed for lift truck applications. Antenna 3 was Huber+Suhner SPA 860/65/90/0/V linearly polarized planar antenna, with 9 dBi gain.
TABLE II
READING RESULTS OF CLAMP TRUCK INTEGRATED READER WITH THREE ANTENNAS, WHEN REELS WERE ON A MAFI TRAILER

<table>
<thead>
<tr>
<th>Reel number</th>
<th>Grabbing direction</th>
<th>Antenna 1</th>
<th>Antenna 2</th>
<th>Antenna 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (S)</td>
<td>35-36</td>
<td>39-40</td>
<td>32-36</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>28-31</td>
<td>28-32</td>
<td>28-30</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>39-40</td>
<td>29-30</td>
<td>27-30</td>
</tr>
<tr>
<td>5</td>
<td>1 (S)</td>
<td>28-29</td>
<td>28-31</td>
<td>29-30</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>28-29</td>
<td>-</td>
<td>28-29</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>-</td>
<td>28-30</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig. 19. Reel locations and tag directions on a mafi trailer, when grabbed from side with clamp truck.

Fig. 20. Three tested antennas attached to paper reel clamps.

Fig. 21. Two stacked reels 3 and 6 grabbed together in truck clamps.

The results of separate reel identification with each antenna can be seen from Table II. In single reel cases (reel 1, 2, 4, and 5), each antenna was able to identify the grabbed reel every time, regardless of tag direction. When two stacked reels were grabbed together to truck clamps, as seen in Fig. 21, antenna 1 and antenna 3 identified upper reel, and antenna 2 identified the lower reel. The presented values are average succeeded identifications per second.

In addition, reel number 2 was grabbed from eight different directions, and the identification was verified with each antenna. The results can be seen from Table III. The presented values are average succeeded identifications per second.

C. Reading Tests on the Mafi Trailer

The purpose of the testing was to find out how efficiently the paper reels tagged with the C-type tag could be identified when they were pulled on a carriage through an RFID gate. The width of the reels was 880 mm and the diameter was 960 mm. Paper quality was offset printing paper. All the 14 tags had different EPC code which was then linked with the reel number. The tests were performed in the port environment and as a transportation fleet there were used a terminal tractor with a mafi trailer (SWL 50 tons). Fourteen reels were unitized onto the mafi trailer and they were put to a certain loading pattern, which is presented in Fig. 22. Fig. 23 presents the setup of the RFID gate.

During the identification tests the distance of the RFID reader antenna from the surface of the moving reels was changed to
TABLE III

**TABLE III**

<table>
<thead>
<tr>
<th>Antenna number</th>
<th>Grabbing direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 (S)</td>
</tr>
<tr>
<td>Antenna 1</td>
<td>-</td>
</tr>
</tbody>
</table>

**TABLE IV**

**MAFI TRAILER READING RESULTS WITH FEIG ELECTRONICS ETSI COMPLIANT READER UNIT**

<table>
<thead>
<tr>
<th>Distance between the reel surface and the reader antenna</th>
<th>Test number</th>
<th>Identification percentage</th>
<th>Reels not identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.35 m</td>
<td>2 tests total</td>
<td>100 %, 14/14</td>
<td>-</td>
</tr>
<tr>
<td>0.50 m</td>
<td>2 tests total</td>
<td>100 %, 14/14</td>
<td>-</td>
</tr>
<tr>
<td>0.75 m</td>
<td>2 tests total</td>
<td>100 %, 14/14</td>
<td>-</td>
</tr>
<tr>
<td>1.0 m</td>
<td>4 tests total</td>
<td>92 %, 13/14</td>
<td>2206</td>
</tr>
<tr>
<td>1.25 m</td>
<td>1st test</td>
<td>92 %, 13/14</td>
<td>2206</td>
</tr>
<tr>
<td></td>
<td>2nd test</td>
<td>86 %, 12/14</td>
<td>2206, 4310</td>
</tr>
<tr>
<td></td>
<td>3rd test</td>
<td>92 %, 13/14</td>
<td>2206</td>
</tr>
<tr>
<td></td>
<td>4th test</td>
<td>92 %, 13/14</td>
<td>2206</td>
</tr>
<tr>
<td>1.50 m</td>
<td>1st test</td>
<td>42 %, 6/14</td>
<td>2206, 4408, 4301, 2201, 2110, 4306, 4406, 4310</td>
</tr>
<tr>
<td></td>
<td>2nd test</td>
<td>42 %, 6/14</td>
<td>2206, 2210, 4306, 2101, 4406, 4310</td>
</tr>
<tr>
<td></td>
<td>3rd test</td>
<td>42 %, 6/14</td>
<td>2206, 2210, 4306, 2101, 4408, 2101, 4410, 4300, 4310</td>
</tr>
<tr>
<td></td>
<td>4th test</td>
<td>32 %, 5/14</td>
<td>2206, 2210, 4306, 2101, 2110, 4306, 4406, 4310</td>
</tr>
<tr>
<td>1.75 m</td>
<td>1st test</td>
<td>28 %, 4/14</td>
<td>2108, 2106, 4401, 4410</td>
</tr>
<tr>
<td></td>
<td>2nd test</td>
<td>28 %, 4/14</td>
<td>2108, 2106, 4401, 4410</td>
</tr>
<tr>
<td>2.0 m</td>
<td>1st test</td>
<td>28 %, 4/14</td>
<td>4308, 4401, 2106, 4410</td>
</tr>
<tr>
<td></td>
<td>2nd test</td>
<td>21 %, 3/14</td>
<td>2106, 4401, 4410</td>
</tr>
<tr>
<td>2.25 m</td>
<td>1st test</td>
<td>0 %</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2nd test</td>
<td>7 %, 1/14</td>
<td>4401</td>
</tr>
</tbody>
</table>

Linearly polarized ETSI frequency band reader antennas with 9 dBi gain and 12-m long cables between the reader unit and the antennas were used (cable losses are larger than usually).

Fig. 22. Identified reels on the mafi trailer and the order of the reels.

clarify how the reading distance affects the identification reliability. The tests were performed by changing the reading distances between 0.35–2.25 m from the antennas to the surface of the reels. Each reading test was repeated 2–4 times. Different RFID reader units were used: Impinj FCC compliant and Feig Electronics, ETSI compliant reader unit. The reader antennas were linearly polarized.

Tables IV and V present the results of RFID gate testing with different types of reader units and antennas. With ETSI compliant reader unit one reader antenna at each side of the gate was used (a total of two reader antennas). It should be noted that in this case 12-m long cables between the reader unit and reader antennas were used which leads to larger power losses than usually. Only one reader antenna on the other side of the gate was used with the FCC compliant reader unit and FCC compliant reader antenna. Thereby the maximum number of identified reels was 7.

It was found out that with increasing reading distance the direction of the IC chip relative to the reader antenna has an effect on the identification of the reels. The most challenging identification case occurs when the IC chip points away from the reader unit (direction 5 in Fig. 9).

Fig. 23. The setup of the RFID gate in the port warehouse.
In the near future, the main emphasis of the research will be on verifying and improving the performance of passive UHF RFID systems in paper industry applications. Novel reader antennas for clamp trucks based on the idea of perpendicular beam scanning which is presented in this paper will be developed. Identification of paper reels will also be tested with AGV integrated reader unit. Paper reel tags will be further optimized to facilitate identification of reels with differently sized reel cores. In addition, the information management architectures in paper reel supply chain and integration of reader units and reader antennas to paper handling machinery will be studied further.

REFERENCES


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