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Automated Identification of Plywood Using Embedded Inkjet-Printed Passive UHF RFID Tags

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***Abstract*—The use of passive ultra high-frequency (UHF) radio frequency identification (RFID) integrated into plywood boards is proposed to enable the identification and tracking of individual plywood boards and end products of plywood. For the first time, tags are embeddable inside plywood by direct inkjet-printing tag antennas on pure birch veneer. The use of passive UHF RFID technology in the applications of plywood industry is discussed, two tag antenna designs for plywood are presented and the tag fabrication procedures are described. Furthermore, results from tag performance measurements performed in the authentic application environment as well as in anechoic conditions are presented and discussed. Measurements show that tags printed on veneer and embedded inside 2 mm thick plywood board exhibited theoretical read ranges from 7.9 to 10.1 meters. The read ranges obtained meet the demands of the plywood industry and offer reliable identification even in challenging environments.**

***Note to Practitioners*—The use of integrated UHF RFID technology embedded inside plywood could bring significant benefits to the plywood industry. At the moment, identification and tracking are done manually or by using bar codes on large shipments of plywood. Manual identification can lead to misreads and external bar codes are easily detached or damaged. In this paper, we propose a solution to directly inkjet-print RFID tags on veneer. After printing, they can be embedded inside plywood. As a result, individual plywood boards are identifiable and traceable during their whole lifetime, even in their end product form. This paper discusses the benefits and challenges of passive UHF RFID technology in the plywood industry, explains the tag fabrication procedures and presents the measurement results of plywood-embedded tags. Results show that the tags are readable from several meters, even inside thick plywood boards. Thus, embedded RFID technology could be utilized by the industry as well as by the end users of plywood as an efficient and reliable automated identification method for plywood boards and plywood-made products.**

***Index Terms*—Plywood industry, radio frequency identification (RFID), inkjet.**

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I. Introduction

THE plywood industry needs an automated identification system which would provide identification and tracking of plywood boards throughout their whole lifetime: from production and warehousing to end products. Every point of the supply chain involves vendors and suppliers who may need to know all details about the board at hand. In addition, often there is a need for identifying products in their end use, e.g., in a case of a customer complaint. Nowadays, identification during production and warehousing is mainly done manually by using various codes to indicate the type, production date, and batch of plywood boards. The packages of plywood are bar coded after the goods leave the factory for further processing. Manual identification is prone to errors and misreads that could lead to delays or wastage. Also, external bar code labels can be easily damaged or lost.

In this paper, embedded RFID technology is used to solve identification problems in the plywood industry for the first time. RFID has been previously been applied for forest industry, in wood log supply chain [1]–[4]. Also, promising results in use of RFID technology in paper industry have been achieved [5].

Passive UHF RFID systems operate around 860–960 MHz frequency band [6]. The operation is based on the coupling of electromagnetic waves that are used for communication and to provide operating power for the tags. A typical system consists of three main components: readers, reader antennas and tags, which are attached to objects that are tracked and identified based on the electronic product code (EPC) [7]–[9]. A reader unit is essentially a transceiver used to communicate wirelessly with the tags. Data from the tags is relayed from the reader to the end application, e.g., a database using an USB or an Ethernet port. A tag contains two components, an antenna and an integrated circuit (IC). The IC consists of a rectifier, modulator and memory. The memory stores the unique electronic identification code.

In the case of embedding RFID tags inside plywood boards, the tag needs to be thin, small, and its coating needs to be compatible with the adhesives used to bond veneer into plywood to prevent the plywood gluing from popping open. In our proposed solution, the tags are fabricated using inkjet-printing that allows passive UHF RFID tags to be embedded inside plywood boards. This allows the tagging of individual boards and as the tag is already inside the board, the end products of the plywood are also identifiable and traceable.

This paper concentrates on analyzing the use of inkjet-printed passive UHF RFID tags in plywood board identification and presents tag designs for direct printing on veneer. Also, the plywood industry as the application environment for passive UHF RFID technology is discussed: Benefits, challenges and opportunities are listed. Moreover, the inkjet fabrication process is described and results from various measurements performed on the embedded tags are presented.

II. Passive UHF RFID in the Plywood Industry

This section introduces the plywood manufacturing process and operation principle of a passive UHF RFID system. Furthermore, it discusses the benefits, challenges, and requirements related to the use of UHF RFID technology in the plywood industry. Finally, the approach to directly print tags onto veneer and embed them inside plywood boards is presented.

A. Plywood Manufacturing Process in Brief

Plywood is made from thin sheets of wood veneer that are glued together with adjacent plies having their grain at right angles to each other. Plywood production requires a high-quality log, which is peeled into sheets of veneer that are then cut to the desired dimensions. These veneers are then dried, glued together, precompressed, and then baked in a press to form the plywood panel. The panel can then be patched, resized, sanded or otherwise refinished, depending on the application for which it is intended.

Typical end uses of plywood are, e.g., floors, walls and roofs in house constructions and transport vehicles, wind bracing panels, packages and boxes, fencing, scaffolding materials, die-cutting boards, and furniture. More information can be found e.g., in [10]–[12].

B. Benefits of Passive UHF RFID Technology in the Plywood Industry

Commonly used barcode technology helps keep track of products that they identify, and hence provide all the necessary information about them. However, barcode readers require a direct line of sight to the printed barcode, where as RFID readers do not require a direct line-of-sight. Thus, RFID tags can be read through various materials, at much greater distances and they can be read much faster. In addition, the printed barcode must be exposed on the outside of the product, where it is subject to greater wear and tear.

RFID tags can be integrated within the product itself, where they are sheltered. In the case of plywood, the safest place for the tag would be inside a plywood board, where it can stay the whole lifetime of the plywood product. Thus. all the relevant data related to the products can be saved and tracked using a database in real time, even at item level. Furthermore, the RFID IC can store additional data if needed. These facts help avoiding counterfeiting and the wastage of the plywood end products, for example, in the case of design furniture.

In addition, RFID-based warehouse management can eliminate current drawbacks with the help of advanced scanning that improves supply chain visibility and agility for greater operational efficiency.

Last but not least, RFID offers a great help for after-sales services. When a customer files a complaint, the manufacturer needs to check all the information on manufacturing, transportation, and storage of a specific board. With an integrated RFID tag, the board can be quickly identified even in its end product form after many years in field use.

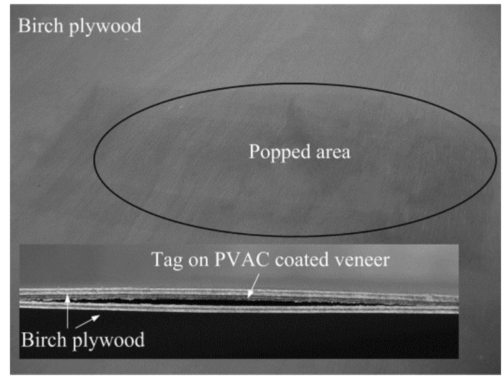

Fig. 1. A rejected plywood board and a cross-section of the popped board.

C. Challenges in Embedding RFID Tags Into Plywood

In the case of embedding RFID tags inside plywood boards, the tag needs to be thin, small and its coating needs to be compatible with the adhesives used to bond veneer into plywood to prevent the plywood gluing from popping open.

It was found out that commercial RFID labels caused the gluing to pop open during the pressing of the board. Also, RFID tags that were printed on Polyvinyl acetate (PVAC) adhesive (thickness$\sim$135–140 μm) which was first added to plywood substrate, had the same effect on the gluing. This happened with both dry sheet glue and wet glue. See Fig. 1, where the top of the rejected plywood board and a cross-section of the board are shown.

The reason for such failure is due to the incompatibility of the PVAC coating with the adhesives used in the veneer bonding process (phenol resin and urea formaldehyde [10]). Commercial tags are coated with a variety of polymers that can also cause failures in the veneer bonding. Also, the thickness of the commercial, polymer coated tags is too large for plywood-embedding.

D. Requirements for the Read Range of RFID Tags

Due to the requirement of identification of the plywood boards in warehouse conditions, many boards on top of, next to, and behind each other need to be identified reliably. A read range of a few meters is sufficient for plywood board identification in the plywood industry and much longer read ranges would not give significant benefits to the supply chain management of plywood boards or for identifying boards during field use and after-sales services.

E. Embedding RFID Tags Into Plywood Using Direct Inkjet-Printing

To overcome the difficulties in the veneer bonding, tag antennas need to be fabricated directly on pure, noncoated veneer. Such fabrication is only possible by means of additive fabrication methods such as screen printing or inkjet-printing [13].

Inkjet-printing was chosen for this study, as the metallization produced by the conductive ink was found to be compatible with the adhesives used in the veneer bonding process, i.e., veneer attachment was successful. The compatibility was enabled by the surface properties of the ink and by the low thickness of the ink metallization layer. Inkjet-printing already also has a proven track record of producing high-performance tag antennas on a variety of substrate materials [14]–[16].

Inkjet-printing technology is not just a single technique, but a collection of several technologies, which all aim the same target, i.e., forming small droplets and guiding them onto the substrate in a controlled way. In inkjet technology, small droplets (500 fl–2 nl [17]) are formed in the printhead and ejected on the substrate. Inkjet-printing allows the use of low viscosity inks, which is extremely important, since it allows for the formulation of inks that only contain active material and solvents without the need for binders. In addition, inkjet allows cheap and contact-free manufacturing based on digital images. However, inkjet-printing tends to be slow, and high throughput is only achieved by using large numbers of heads in parallel. This, in turn, has introduced yield concerns related to the misfiring of individual heads during printing of a pattern. The ejection of droplets, fluid pressures, and the movement of print stage or printheads are controlled. Drop form and velocity are controlled with the printhead parameters and the right values depend on material properties and interactions between the material and the printhead. The substrate must be at the correct position when the drop lands on the substrate. Overall, several process conditions must be in control for inkjetting to succeed [17], [18].

Inkjet utilizes liquid materials, which sets some material requirements. The fluid should have certain viscosity (typically values between 8 and 25 Pa·s) and surface tension values (should remain between 2.8–3.3 N/m). Obviously, the requirements are also affected by the desired interaction with the chosen substrate [18]. To be used in inkjet-printing, small particles are needed. Thus, nanosize particles are used in inkjet ink formulations. The main material currently used for conductive inks is silver but there are also other options for inkjettable metallic inks, e.g., nanoparticle copper, nickel, and gold inks.

Benefits of inkjet-printing in manufacturing antennas during productive process of plywood are that it is cost-efficient, since no materials are wasted and no masks are needed, and fast, since the patterns are formed from digital images. These facts enable a single printer to print countless types of planar tag antenna designs on the plywood boards. Therefore, boards can be equipped with application-specific type of tags, which are optimized for a given environment, geometry or material type.

After inkjet-printing the tag antennas, the RFID IC is attached using wire bonding, tape carrier package, flip chip, etc. A direct attachment of the IC with electrically conductive adhesive (ECA) bonding would probably be ideal because of a low-temperature process and low cost. In the future, the attachment of the IC could be also done directly by inkjet-printing the adhesive on the tag antenna's IC pads as jettable ECAs become available [19].

The temperatures and pressures used in the process are tolerable by the inkjet-printed tag antenna and IC. If the tag is assembled already before veneer drying, it can be sintered during drying. Drying temperatures between 100–160 °C may be considered normal. The dried veneers are glued together, precompressed, and then baked in a press to form the plywood panel and thus the tag can already be used to identify the veneer at all stages of the manufacturing process.

III. Tag Antenna Designs for Veneer

This section discusses design considerations for tag antennas that are printed directly on veneer and presents two tag antenna designs developed for birch veneer.

A. General Design Considerations for Inkjet-Printed Tag Antennas on Veneer

A veneer surface is a challenging surface for inkjet-printing due to its porosity and high surface roughness. The ink droplets are easily absorbed by the wood, preventing the nanoscale metallization particles, which are contained within by the ink, to form a conductive layer.

A unique characteristic of wood and veneer surfaces are their grain. A close-up examination of the grain reveals that the surface has valleys and hills that vary according to the grain. In the direction of the grain such variations in the surface are low, whereas against the grain variations in the surface roughness are significant. Therefore, to maximize the performance and fabrication process throughput, tag antennas should be printed in layers in the direction and against the grain. In fact, tag antennas printed only in one direction did not function even with several layers of conductive ink.

Our preliminary tests showed also that tag antennas which had the antenna geometry printed along the grain showed the best performance. Tag antennas printed on wood should be therefore designed so that most of the surface area in the antenna is located on one axis, in the direction of the grain. This "one axis design rule" has been one of the main design aspects in the tag antenna's presented in Section IV.

The spread of the ink on the plywood surface is also a major concern. The ink spread is the highest in the direction of the grain. Therefore, tag antenna designs should be optimized so that there are no narrow gaps in the direction of the grain as the ink spread can cause short circuits in these areas. The amount of ink spread is related to the size of the grain as well as on the printing resolution, which should be kept as low as possible.

B. Tag Antenna Design Parameters

The design goals for tag antennas for veneer were to achieve an omnidirectional read pattern and long read range. The first of these goals meant that two types of planar tag antenna types were available: a slot or a dipole antenna. A slot type tag antenna requires significantly more metallization and a larger foot print than a dipole. This led us to choose the dipole as it can be manufactured with lower production costs.

The maximal read range of a passive UHF RFID tag depends on the sensitivity of the RFID IC as well as on the gain and quality of impedance matching between the tag antenna and IC [20], [21]. The read range of an arbitrary tag can be optimized by selecting an IC with low-power consumption, maximizing the antenna gain, and arranging a complex-conjugate impedance

TABLE I
PARAMETERS USED IN HFSS 13

Parameter	Value
Dielectric constant for birch plywood ε_r	2.2 (at 0.8-1 GHz)
Loss tangent δ for birch plywood	0.1 (at 0.8-1 GHz)
Plywood thickness on front | back side of the antenna	1 mm | 1 mm
Plywood size	300 mm by 300 mm
Ink conductivity	25 MS/m
Ink layer thickness	5 µm
RFID IC input impedance*	15-j150 Ω

example value calculated at 866 MHz

matching between the IC and tag antenna for maximal power transfer [22].

The criteria for a long read range was challenging for two reasons. First, the conductivity and losses generated at UHF frequencies in inkjet-printed conductors inheritably reduce the efficiency of inkjet-printed antennas. Furthermore, plywood is a highly dissipative antenna substrate. Its losses are generally speaking over ten times higher than the losses in more traditional microwave substrate materials.

Losses caused by the inkjet-printed conductor can be minimized by printing multiple overlapping layers of conductive ink [23]. This increases the thickness of the conductor and reduces power losses. Losses caused by the plywood cannot be affected. Thus, the design of the tag antennas was focused on maximizing their radiation efficiencies, i.e., maximize antenna gain, and to optimize the tag antenna impedances to provide good power transfer to the RFID IC.

In the case of tag antennas, the power transfer between the antenna and IC is best described by a power transmission coefficient (PTC) τ, which gives the ratio between powers delivered to the load and reflected back to the generator. Formulation of the power transmission coefficient can be found from [24]. Another quantity describing the operation of a tag antenna is the realized gain which is the gain of the antenna multiplied by the PTC.

Ansys HFSS 13, a finite-element-based 3-D full-wave electromagnetic simulator was used to optimize the two tag antenna structures presented in this paper. The antennas were optimized to operate with a passive Higgs-3 RFID IC from Alien Technology [25], while embedded inside oven dry, two millimeter thick, uniform birch plywood. The parameters used to model the inkjet-printed conductor, silver birch plywood and RFID IC are listed in Table I. The input impedance of the Higgs-3 IC was modeled using a frequency-dependent model from [26] and the dielectric properties of birch plywood were estimated from [27] and [28]. However, it should be noted that the reported values are not constant and they will vary with frequency, temperature, and humidity.

C. Tag Antenna Designs for Birch Veneer

First of the tag antenna designs for birch veneer was designed to exhibit wide operating bandwidth, referred as the *wideband tag antenna*, while obeying the one axis rule described in Section III-A. Tag layout shown in Fig. 2 and key dimensions listed in Table II. The wide operating bandwidth was achieved

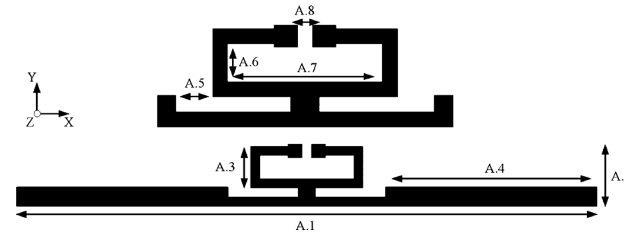

Fig. 2. Dimensions of the wideband tag antenna design for birch veneer.

TABLE II
KEY DIMENSIONS OF THE TAG ANTENNA DESIGNS FOR PLYWOOD

Dimension	Wide band design A. [mm]	Compact design B. [mm]
1	123.9	86.8
2	13.2	7.0
3	9.2	2.5
4	45.1	20.7
5	4.8	2.0
6	5.1	
7	20.0	
8	2.0	

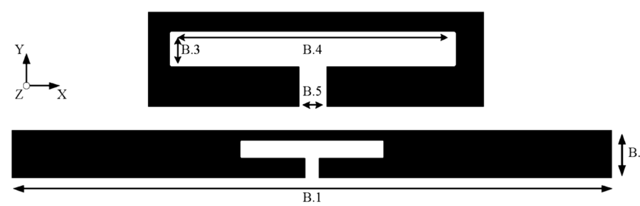

Fig. 3. Dimensions of the compact tag antenna for birch veneer.

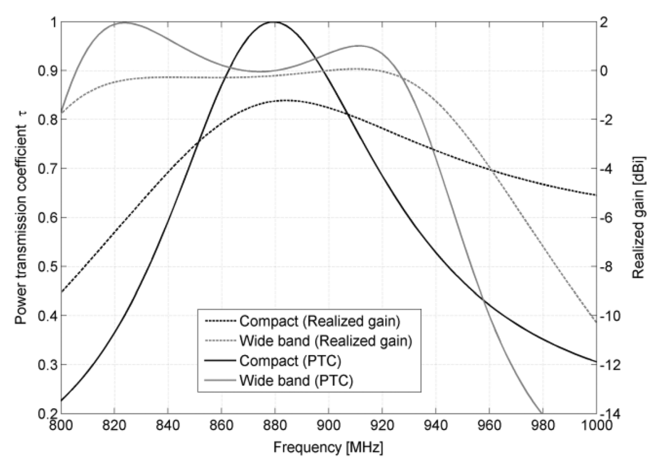

Fig. 4. The power transfer coefficients and realized gain of tag antennas embedded in 2 mm thick plywood.

by using an inductive loop type impedance matching network that provides the complex-conjugate matching [29].

The power transmission coefficient and the realized gain of the tag antenna are shown in Fig. 4. The tag exhibits a wide operation bandwidth of 120 MHz ($\tau \geq 0.9$), which covers the European and US UHF RFID bands.

A second tag antenna design, later referred as the *compact tag antenna*, was created to offer a smaller physical size and faster fabrication time. The layout of the tag is presented in Fig. 3 and the key dimensions of the design are listed in Table II. The tag

TABLE III
KEY PARAMETERS OF THE INKJET-PRINTING PROCESS

Parameter	Value
Jetting voltage	24 V
Jetting frequency	9 kHz
Cartridge temperature	40 °C
Platen temperature	60 °C
Drop volume	10 pl
Printing resolution	423 dpi (60 µm drop spacing)

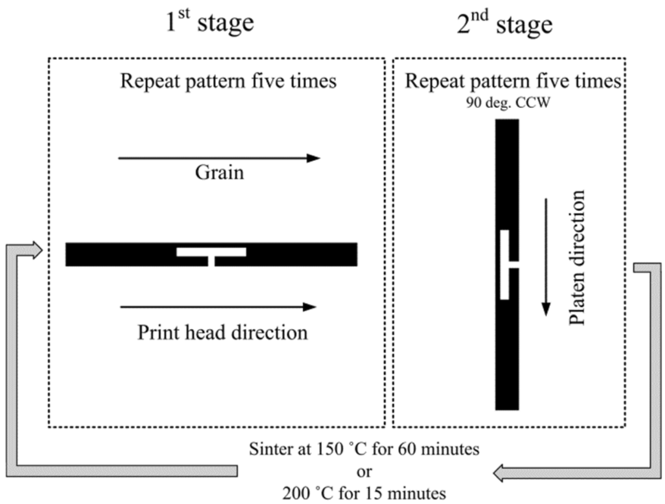

Fig. 5. Fabrication process of the wide and compact tag antennas on pure birch veneer using an inkjet-printer.

antenna's geometry is utilizing the one axis rule more strictly than the wideband tag design and should allow for more reliable printability.

The compact tag antenna's input impedance was complex-conjugate matched to the IC's input impedance using a T-matching network. The power transmission coefficient and the realized gain of the tag antenna are shown in Fig. 4. The tag exhibits a narrow operating bandwidth of 36 MHz ($\tau \geq 0.9$) around the European UHF RFID band. The gain of the compact tag antenna is around -1 dBi at 866 MHz.

IV. TAG FABRICATION PROCESS

Samples of both tag antenna types were inkjet-printed using a Dimatix DMP-2800 material printer equipped with 10 pl print head nozzles. Harima NPS-JL [30], a silver nanoparticle ink, was used as the conductive ink. The substrate used was a 0.4 mm thick sheet of birch veneer. The key parameters of the inkjet-printing process that produced minimal ink spread are listed in Table III.

NPS-JL is especially suitable for the plywood fabrication process as it requires low sintering temperatures, 120 °C minimum. Sintering is required for the nanoparticles to adhere to each other thus forming a conductive layer. The resistivity of NPS-JL is dependent on the sintering temperature and ranges from 4–6 $\mu\Omega\cdot$cm [30]. This is approximately three times higher than the resistivity of bulk silver.

The fabrication process of the samples made for this study is described in Fig. 5. At the first stage of the process, the tag antennas were printed in the direction of the grain using five layers of ink. At the second stage, additional five layers of ink were

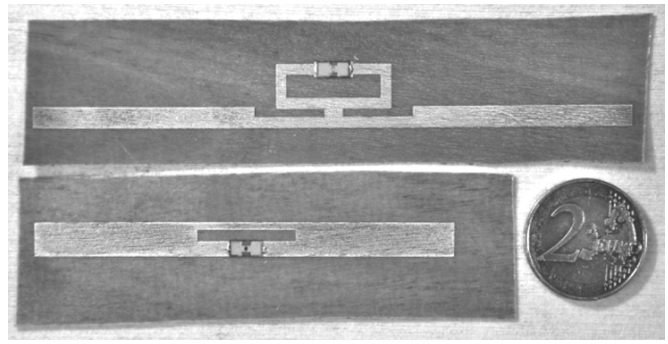

Fig. 6. Inkjet-printed samples of wide and compact tag antennas with Higgs-3 ICs on plywood.

added in the direction against the grain. This ensures that the plywood grain is fully filled with ink. It was found that without the second stage, samples printed on pure plywood were not working, not even with ten layers of ink printed in the direction of the grain.

After the second stage, samples were sintered at 150 °C for 60 min. After sintering, the abovementioned process was repeated again to ensure sufficient conductor thickness for the antennas. After printing, Higgs-3 RFID ICs were attached to the samples using a conductive silver epoxy resin. Fig. 6 shows a picture taken from both fully fabricated, inkjet-printed tags.

The fabrication process can be accelerated by sintering the samples at 200°C for 15 min in the first curing stage. The final sintering should be done for full 60 min to maximize the conductivity of the ink layer. Furthermore, the amount of pattern repetitions can be reduced by using printed nozzles with higher drop volumes.

After inkjet-printing and attaching the ICs, the tags were embedded inside a 2 mm thick, 40 cm by 40 cm sheet of plywood. The compact tag was embedded using wet glue, while the wideband tag was embedded using dry sheet glue to confirm that both methods are suitable. The attachment of the plywood layers was done at 140 °C for 300 s using a pressure of 15 bar.

V. MEASUREMENT RESULTS

This section presents results from measurements that were performed to characterize the performance of the plywood-embedded inkjet-printed wide and compact tags in various conditions.

All of the measurements made for this study were performed using Tagformance measurement unit from Voyantic Ltd. The core operations of the measurement device are performed with a vector signal analyzer. Tagformance was used to measure two key properties of passive UHF RFID tags: threshold power and theoretical read range. Both quantities can be measured as a function of transmit frequency or as a function of tag to reader antenna angle at a point frequency.

Threshold power describes the minimum transmit power, at the transmit port, to activate the tag. Threshold power of an arbitrary tag can expressed as

$$P_{\text{TS}} = \frac{P_{\text{IC}}}{G_{tx} G_{\text{tag}} \tau \left(\frac{\lambda}{4\pi d}\right)^2 \left| p_{tx}^{\wedge} \cdot p_{\text{tag}}^{\wedge} \right|^2} \quad (2)$$

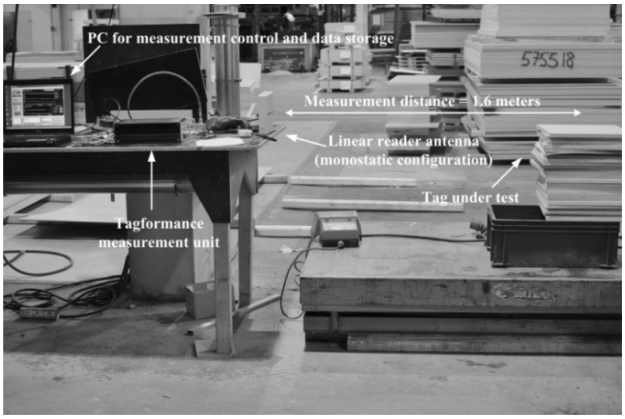

Fig. 7. Measurement setup at the plywood factory.

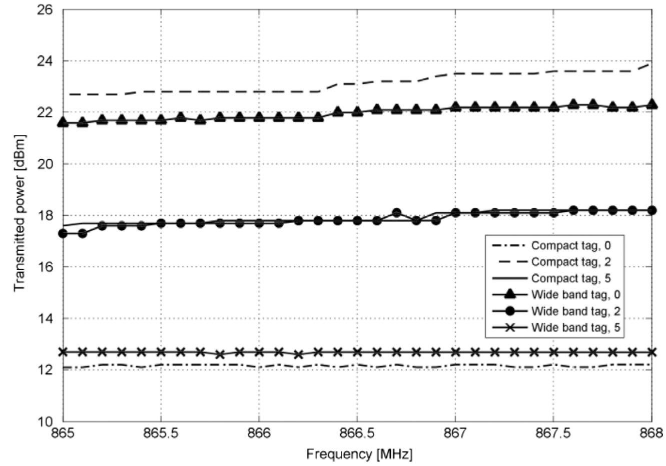

Fig. 8. Threshold sweep results acquired at the plywood factory.

where P_{IC} is the sensitivity of the RFID IC, G_{tx} and G_{tag} are the gains of the reader and tag antenna, d is the distance between the tag and reader antenna, p_{tx} and p_{tag} the unit electric field vectors of the transmitting antenna and tag antenna. The inner product of the electric field vectors describes the power loss due to possibly mismatched polarization planes between the reader and tag antenna.

Theoretical read range describes the maximal distance between the tag and reader antenna in free space, i.e., environment without reflections or external disturbances; hence the term theoretical read range. Tagformance measurement system is able to calculate the theoretical read range of a tag using its measured threshold power along with the measured forward losses. The forward loss describes the link loss between the generator's output port to the input port of an equivalent isotropic antenna placed at the tag's location. The forward loss from the transmit port to the tag, is calculated using a reference tag during the calibration procedure of Tagformance. Theoretical read range is calculated assuming that the read range is limited by the maximal allowed transmitted power levels. Theoretical read range can be therefore calculated using the following expression:

$$d_{\mathrm{Tag}} = \frac{\lambda}{4\pi}\sqrt{\frac{\mathrm{EIRP}}{\mathrm{P_{TS}L_{fwd}}}} \tag{3}$$

where EIRP is the maximum equivalent isotropically radiated power allowed by local regulations, 3.28 W in Europe, P_{TS} and L_{fwd} are the measured threshold power and forward losses correspondingly.

A. Threshold Power of Plywood-Embedded Tags at the Plywood Factory

The first measurement focused on determining if the tags had remained operational after they had been embedded in the plywood sheets at the plywood factory. Furthermore, the measurement studied if the factory environment would allow distortionless measurements at the European UHF RFID band.

The measurement setup where the reader and tag are faced at the factory is shown in Fig. 7. Tagformance measurement unit was used in a monostatic configuration, i.e., a single linearly polarized reader antenna (6 dBi gain) was transmitting and receiving power. The measurement distance was 1.6 meters.

The acquired threshold power levels from both tag types are shown in Fig. 8. The index shown in the legend describes the number of 18 mm thick birch plywood boards stacked on top of the tags. The results verify that the fabricated embedded tags are readable in their proper application environment and that both tag types remained operational after the plywood bonding process. Both tags are readable from 1.6 meters, even when additional plywood is added on top of the tags.

B. Threshold Power and Theoretical Read Range of Non-Embedded and Plywood Embedded Tags

The threshold power and theoretical read ranges of the samples were measured before and after embedding them inside the plywood from 800 MHz to 1000 MHz in a compact anechoic chamber. Tagformance measurement unit was used in conjugation with a 6 dBi linear patch antenna. The measurement distance was 45 cm.

Fig. 9 shows a comparison between the threshold power levels and theoretical read ranges of both tag types on 0.4 mm thick birch veneer and once embedded in the center of a 2 mm thick plywood layer.

The compact tag is showing its highest read ranges at the European UHF RFID band once embedded. The peak read range of 7.9 meters is found at 870 MHz. The wideband tag has a wider bandwidth of higher read range than the compact tag as expected. The wideband tag could be tuned toward higher frequencies for added read range performance throughout the whole global UHF RFID band. The peak read range of 10.3 meters is found at 838 MHz.

C. Threshold Power and Theoretical Read Range of Plywood Embedded Tags in a Stack of Birch Plywood

During warehousing, the embedded tags will be placed in piles of plywood boards or embedded in plywood-made objects of varying thickness. In this case, the amount of plywood around the tag can be drastically different from the original antenna design conditions.

To evaluate the effect of added plywood layers, pieces, 18 mm thick 40 cm by 40 cm, of birch plywood (24 °C, 14 wt%) were added underneath and on top of the samples. The tag under test

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

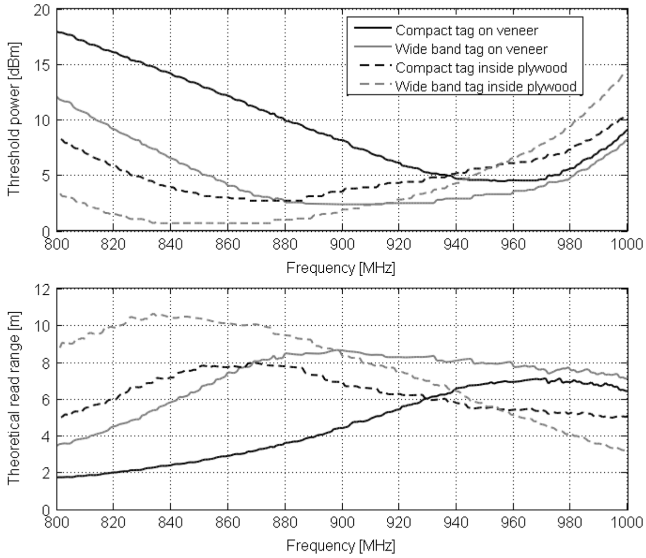

Fig. 9. Threshold and theoretical read range of non-embedded and plywood-embedded samples.

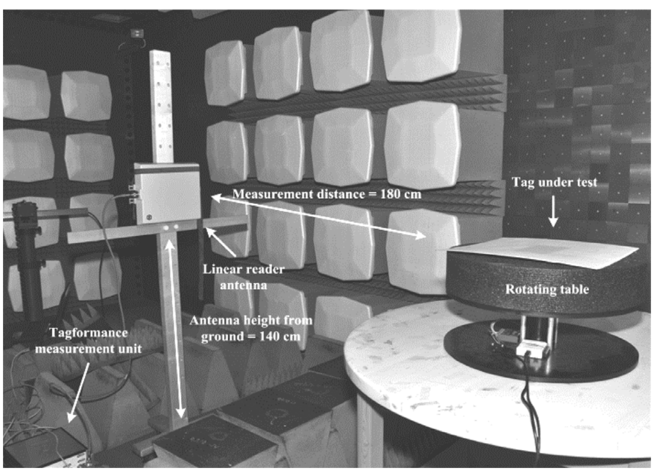

Fig. 10. Measurement setup in the anechoic room before additional plywood is added underneath and on top of the sample.

was placed in the center of the plywood board stack. The monostatic measurement setup inside an anechoic room before additional plywood is added underneath and on top of the sample is shown in Fig. 10.

Figs. 11 and 12 present the threshold levels and theoretical read ranges of the compact and wideband tags once additional plywood is added. The number of birch plywood pieces added are indicated in the figure legends using a notation *number of pieces underneath* | *number of pieces on top* of the sample.

The embedded compact tag, in Fig. 11, exhibits excellent robustness towards the amount of plywood around it. The tag is readable from over 5 meters throughout the whole global UHF RFID band.

The results obtained with the wideband tag are shown in Fig. 12. The effects of the added plywood are more significant in this case. The tag is readable from a distance of 3.1 meters at 866 MHz once 90 mm of plywood is added on both sides. In this case, the tag is readable throughout the global UHF RFID band from a distance below 1.8 meters.

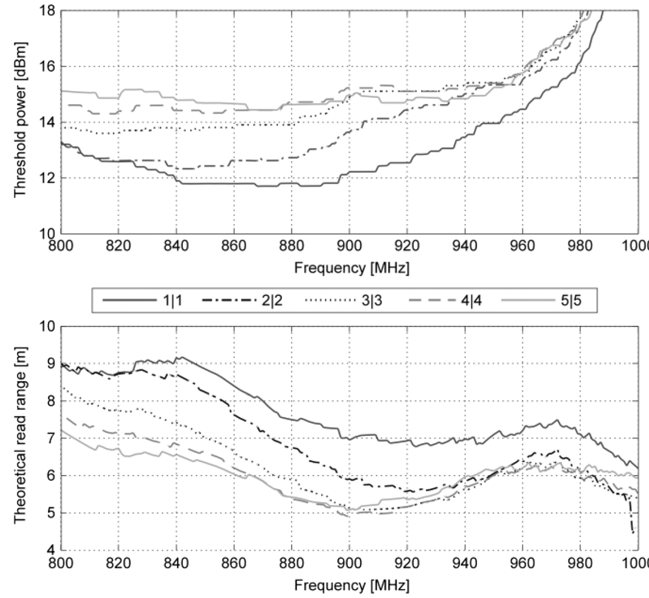

Fig. 11. Threshold and theoretical read range of the compact band tag in different plywood configurations.

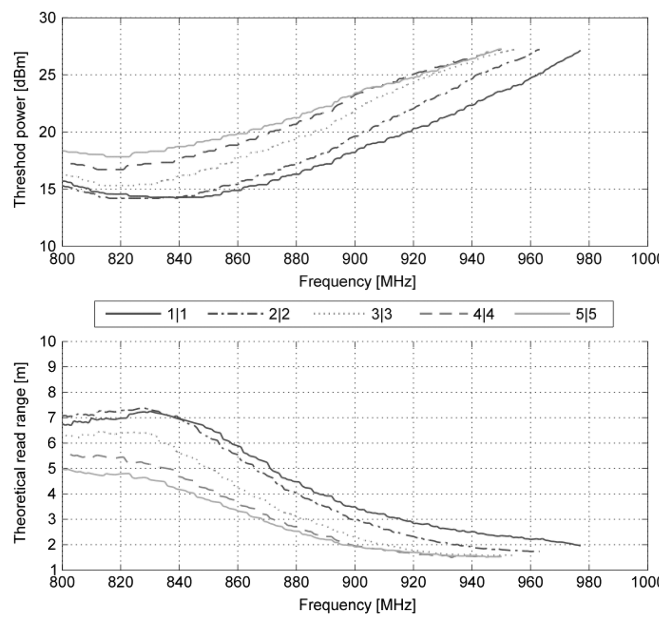

Fig. 12. Threshold and theoretical read range of the wideband tag in different plywood configurations.

Table IV lists the obtained theoretical read ranges of both plywood-embedded tag types at the center frequency of the European UHF RFID band. The results show that the decrease in the read range of the tags gets gradually smaller as more plywood is added. The drop in the read range is showing a gradually decreasing trend. Therefore, the tags should be readable from a few meters away, even when stacked in to tall piles of plywood board or when embedded in thick layers of plywood.

D. Radiation Patterns of Inkjet-Printed Plywood-Embedded Tags

Results presented in previous sections were obtained from a fixed angle (the angle of the highest read range) between the

TABLE IV
EMBEDDED TAG READ RANGE AT EUROPEAN UHF RFID BAND

Measurement conditions	Compact tag read range at 866 MHz	Wide band tag read range at 866 MHz
FS I FS	7.9 m	10.1 m
18 mm I 18 mm	8.1 m	5.5 m
36 mm I 36 mm	7.4 m	5.0 m
54 mm I 54 mm	6.4 m	3.9 m
72 mm I 72 mm	6.1 m	3.4 m
90 mm I 90 mm	5.9 m	3.1 m

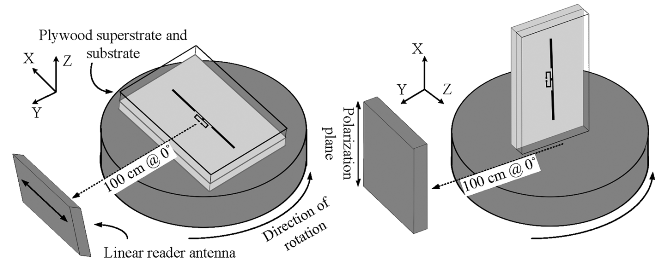

Fig. 13. Illustration of the radiation pattern measurement setup: On the left XY-plane pattern measurement, on the right YZ-plane measurement setup (tag in the center of the plywood sheet).

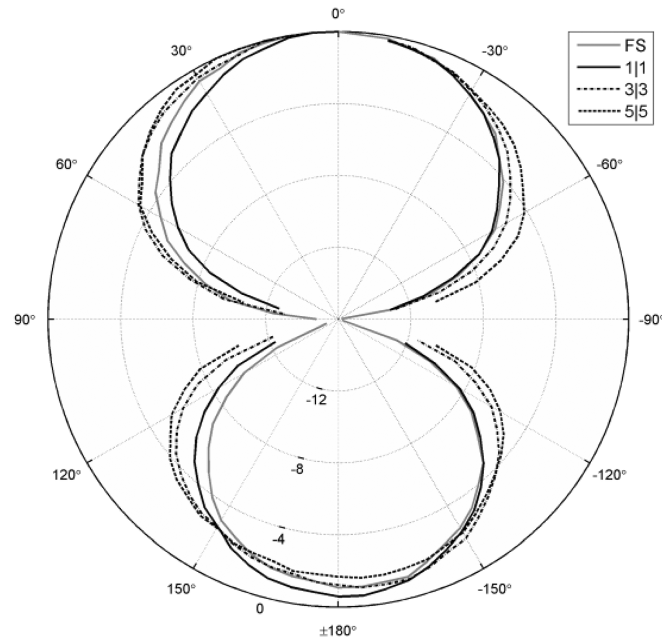

Fig. 14. XY-plane radiation patterns of the compact tag in center of the plywood stack.

reader antenna and tag. However, in previous studies it was noticed that in practice the tags are not always read from this angle [31]. This has significant effects on the readability of tags since read range is dependent on the read angle. Furthermore, the way the tags are positioned in the plywood sheets and the size and wood type of the plywood have effects on the readability from different angles [32]. These effects are due to reflections and refractions of the electromagnetic waves by the plywood layers as well as due to the changes in the tag antenna's current distribution and magnitude.

This section presents the radiation patterns of the compact tag in two plain cuts and in two different positions on the plywood sheet: in the center of the plywood sheets and in the edge of the sheet. Both tag types, the compact and wideband, are equipped with a dipole antenna so the results shown are valid also for the wideband tag.

The radiation patterns were measured first in free space, followed by measurements where the tag was mounted in between additional, 18 mm thick, 40 cm by 40 cm long birch plywood sheets. The amount of sheets is indicated in the results by a notation *number of pieces underneath* $|$ *number of pieces on top* of the sample. FS indicates the free space result, i.e., embedded-tag without additional plywood layers.

The presented radiation patterns are the XY- and XZ- plain cuts, shown in Fig. 13, at 866 MHz that are normalized to the lowest threshold power level [33]. The measurement setup was similar to the one in Fig. 11, with the exception of measurement distance which was reduced to 100 cm.

The XY-plane radiation patterns of the inkjet-printed plywood-embedded tag, once positioned in the center of the plywood sheet, are shown in Fig. 14. The pattern shows the inherent nulls of the dipole in the pattern at 90° and 270° angles: The tag cannot be read if the dipole ends are facing the reader antenna. Adding additional plywood layers does not change the shape of the pattern significantly; however areas where the tag is non-readable get larger as more plywood is added. The small difference between the 0° and 180° readings is due to the slight asymmetry of the tag antenna: the highest read range is found when the IC is pointing toward the reader antenna.

The YZ-plane radiation patterns of the inkjet-printed plywood-embedded tag, once positioned in the center of the plywood sheet, are shown in Fig. 15. The free space pattern is omnidirectional, a characteristic of a dipole antenna. However, once additional plywood layers are added the patterns change dramatically and lose their omnidirectionality. The results show that the tag is the most readable from directions parallel with the plywood sheet. The tag continues to be readable from all directions in the YZ-plane, but additional nulls have formed, causing high threshold levels. As more plywood is added these nulls are getting deeper, i.e., more transmit power is needed to activate the tag.

The XY-plane radiation patterns of the inkjet-printed plywood-embedded tag, once positioned near the edge of the plywood sheet (edge with tag facing towards the reader antenna at angle 0°), are shown in Fig. 16. The tag has the highest read range once the edge containing the tag faces away from the reader. The tag antenna has become more directional and is showing a higher gain at angle 180° than in the free space.

The YZ-plane radiation pattern of the inkjet-printed plywood-embedded tag, once positioned near the edge of the plywood sheet (edge with the tag facing towards the reader antenna at angle 0°), is shown in Fig. 17. A similar effect is also visible in the YZ-plane as in the XY-plane: the tag has the highest read range facing away from the reader. As more plywood is added the beam width of the high read range area is made narrower.

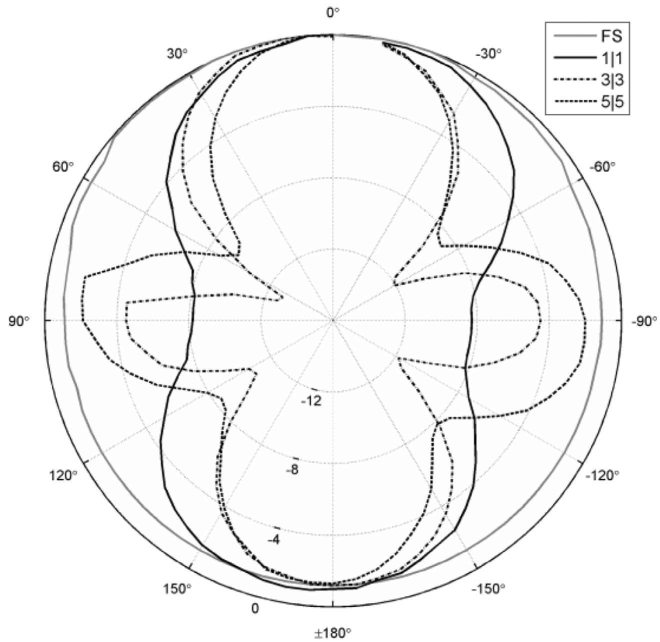

Fig. 15. YZ-plane radiation patterns of the compact tag in center of the plywood stack.

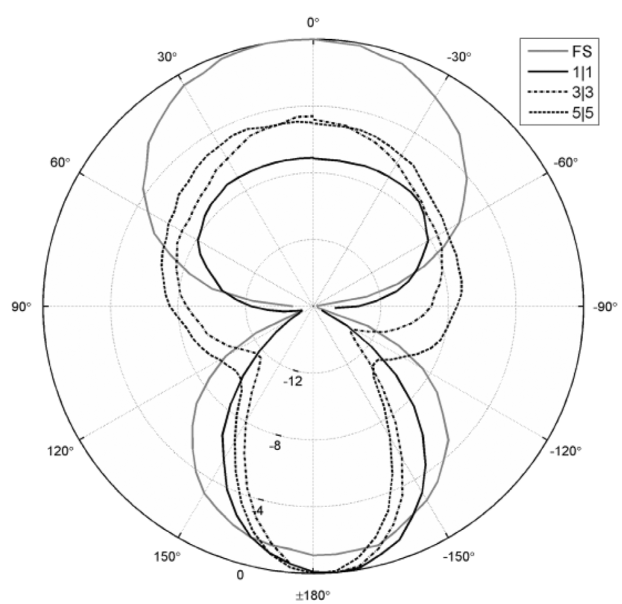

Fig. 16. XY-plane radiation patterns of the compact tag near the edge of the plywood stack.

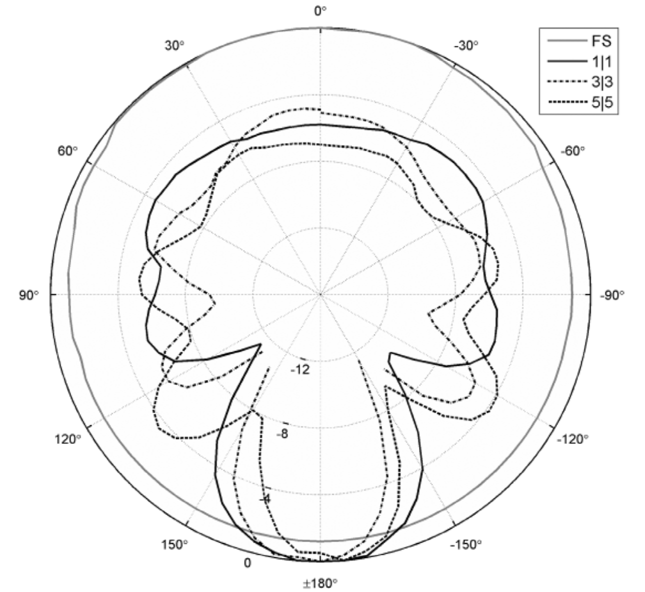

Fig. 17. YZ-plane radiation patterns of the compact tag in near the edge of the plywood stack.

VI. Practical Implications of Measurement Results

This section summarizes the findings of the measurements and discusses their implications for the usability of plywood-embedded tags.

Tags embedded in the 2 mm thick plywood sheet had a theoretical read range of several meters throughout the global UHF RFID band. The results are excellent considering the dissipation of RF power in the plywood and the challenging properties of plywood as a printing surface.

The size and thickness of the plywood stack as well as the positioning of the tags on the plywood sheet had a significant effect on the read range and radiation pattern on the tags. As more plywood is piled on top of the tag, its read range is gradually decreased. This is due to the dissipated power on the plywood as the incident power from the reader is attenuated.

The measured radiation patterns for both tag types show that the omnidirectionality of the dipole type tag antennas are lost once the tags are stacked in piles of plywood. Moreover, the placement of the tag as well as the thickness of the plywood layer determines the shape of the tag's read pattern. The lowest threshold power levels are achievable when the tags are read from direction parallel with the plywood. If placed asymmetrically near the edge of the plywood sheet, the tag is most readable from the direction of the opposite edge, i.e., backside radiation.

The magnitude of backside radiation could be alleviated by optimizing the tag antenna structure to introduce asymmetry in the current distribution that could increase the directivity in the direction of the reader antenna. Alternatively, reflectors could be printed alongside the dipoles to decrease backside radiation.

The nulls at the ends of dipoles can cause readability problems in free space and in the plywood piles if only a single reader antenna is used and if special care is not taken to correctly arrange the tags orientation towards the reader antenna. Therefore, is it advisable that at least two reader antennas are to be used in a right angled configuration to maximize tag readability.

It should be noted, however, that all of the measurements were performed in situations where there were no adjacent tags in close proximity. In practice and in the application of the plywood-embedded tags, several tags may lie in close proximity in the plywood piles. As tags are brought closer to one another, their operation characteristics can alter significantly [34], [35]. When multiple RFID tag antennas are placed close to each other, each antenna behaves like a shielding and reflecting object to others and the radiation pattern and other electromagnetic properties can be detuned. The stacking impact often leads to performance degradation. If the mutual coupling effect is not taken into account when stacking the sheets of plywood with embedded tags, the readability of the tags could be severely degraded [34].

Next step is to characterize the system in realistic scenario in addition to the anechoic chamber. An important part of this future research is to examine a situation where several tags are in close proximity.

VII. Conclusion

Inkjet-printed plywood-embedded tags were fabricated for the first time ever using direct inkjet-printing on pure birch veneer and tested for use in the plywood industry and in the end products of plywood. In addition, the benefits, challenges and opportunities enabled by the use of UHF RFID technology in the plywood industry were discussed.

Inkjet-printed tags are needed in this application as the tag antenna needs to be extremely thin and compatible with the adhesives used in the plywood manufacturing process to prevent the popping of the plywood sheets.

It was shown that passive UHF RFID tags are inkjet-printable directly on to veneer and embeddable into plywood. The read range of the inkjet-printed plywood-embedded samples ranged between 7.9 and 10.1 meters at the European UHF RFID band. Moreover, the samples exhibited read ranges of several meters throughout the whole global UHF RFID band. The performance levels of the fabricated embedded tags are more than sufficient for the requirements of the plywood industry and for the end users of plywood-made products: tags are readable from a few meters away even when stacked in tall piles of plywood or embedded inside thick layers of plywood.

Measurements showed that many factors need to be taken into consideration to achieve maximal reliability and performance from tags: Positioning of the tags on the plywood sheets, tag mutual coupling, and the thickness of the plywood boards all have effects on the operating characteristics of passive UHF RFID tags.

Extending this theoretical investigation into realistic scenario is the next topic in future research.

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