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The Effect of Tag Positioning on Passive Radio Frequency Identification (RFID) Performance: Case of Food Beverages

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Smart packaging containing sensors could be considered the natural progression in packaging innovation for many consumer products. The goal of implementing sensors into the packaging is to improve product traceability and sustainability and to increase product shelf-life. Radio-frequency identification (RFID) systems have already been adopted for traceability purposes in many supply chains including apparel, electronics, pharmaceuticals, and food. The Ultra-High Frequency (UHF) range is widely used for those purposes. However, to improve the adoption of this technology several challenges need to be overcome. The goal of this research was to determine the best configuration for attaching a passive UHF RFID tag to different beverage bottles. To do this, three different packaging materials (polyethylene terephthalate (PET), clear glass, and Tetrapak®) which are commonly used in the beverage industries, and three commercially available passive UHF RFID tags with different designs were used. The influence of the RFID positioning (bottom or top) on the performance of tags using empty and water-filled bottles was assessed. Power on tag Forward and Theoretical Read Range were used as the indicators of the tag performance.
The results of this study confirmed that tag positioning affects the performance of the RFID system. In order to have the best passive UHF RFID tag performance, packaging and labeling industries should consider the effect of tag design, packaging material, and food composition.

1. Introduction

In the 20th century, the packaging industry evolved. The application of active packaging including antimicrobials and oxygen scavengers established new precedents to prolong shelf-life and protect food from environmental damage (Han et al., 2018). In recent years, newer systems called smart or intelligent packaging were introduced in which different mechanical, optical, and/or electronic sensors were added to the packaging. The sensor aims to detect and monitor, in real-time, the status of the product across the supply chain (Aliakbarian, 2019).
Radio-frequency identification (RFID) system is one of the technologies that has been widely adopted for traceability purposes in the food supply chain (Dainelli et al., 2008; Chen et al., 2020; Zou et al., 2022). RFID is a wireless communication technology that includes three major components: a chip or tag that includes the information/data, an antenna that transmits the radio frequency, and a reader that communicates between the chip and the antenna. RFID systems can work without any external power source (passive) or with external batteries (active). These devices offer optical systems, such as larger reading distances without the need for line-of-sight, high data storage capacity, and the possibility to read multiple tags simultaneously, but the cost of traditional RFID tags is still too high for many applications involving low-cost items.
Passive RFID tags are cheap and are mostly used to provide accurate information about the geolocation of the products at any time and any point of the supply chain, hence the name track and trace. Often, traceability can be delineated into backward traceability (or tracing) and forward traceability (or tracking), depending upon the intended trajectory of the product. Track and trace are important components of a sustainable and safe supply chain (Chen et al., 2020).

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Ultra-High Frequency (UHF) passive RFID technology is widely used for product track and trace purposes in different fields including the apparel industry and inventory management (Unhelkar et al., 2022). For these applications, UHF RFID must be compliant with the ISO/IEC standards and should be designed to operate in frequency bands from 860MHz to 960MHz. Other than the cost of the RFID sensors, the integration of UHF RFID-based traceability systems in the food and beverage industries represents a major challenge due to the external packaging composition and the high-water content in food composition which all affect the RF devices' performances (Zhang and Li, 2012). Another major issue in the application of the UHF passive RFID at the item level is the ability to operate efficiently in close coupling with the reader antenna in presence of any kind of substrate materials. The material property, packaging type, and size of the tagged item strongly influence the energy-harvesting capability of the RFID tag. Materials that contain a high quantity of lipids are less critical than products containing a high quantity of water. All these limit the possibility of the wide adoption of RFID systems in food industries.

Although researchers (Gonçalves et al., 2014) have assessed the RFID tag performance losses due to the proximity of water and aqueous solutions, there is still the need to further investigate the impacts of packaging type and labeling on the reading range of UHF RFID tagged-products.

The goal of this research was to determine the best configuration for affixing a passive UHF RFID tag to beverage bottles. To do this, three different packaging materials (polyethylene terephthalate (PET), clear glass, and Tetrapak®) were used. These are commonly utilized in the beverage industry. Three commercially available passive UHF RFID tags with different designs and properties were selected. The influence of the RFID positioning (bottom or top) on the performance of tags using empty and water-filled bottles was assessed. The Power on tag Forward and Theoretical Read Range were used as the indicators of the tag performance. Finally, the correlation between power on tag forward and theoretical read range was calculated. The results of this work can be used for deeper investigations on the application of UHF RFID tags on food and beverage packages such as orange juice, apple juice, wine, and milk.

2. Materials and methods

2.1. Materials

Three commercially available UHF RFID tags were collected from AtlasRFIDstore.com. Tags are indicated as Tag 1, Tag 2, and Tag 3, and are shown in Figure 1. All tags have the same dimension.

Figure 1. Different commercially purchased UHF RFID tags are used in this work.

Three different bottles made of clear glass, Polyethylene terephthalate (PET), and Tetrapak® were used. These bottles were purchased at the grocery store and are shown in Figure 2. Before analysis, bottles were washed and dried.

Figure 2. Different commercially purchased bottles were used in this research. From left to right bottles are made of TETRAPAK®, clear glass, and polyethylene terephthalate (PET).

2.2. RFID Performance Testing

All RFID performance measurements were conducted using the C50 anechoic Voyantic chamber and Voyantic Tagformance® measurement system equipped with a rotating platform and a 4-channel antenna array. Samples were placed within the chamber at a fixed distance of 50 cm from the circular antenna array. The antenna array includes four antennas each oriented with an additional 30° angle to the previous one (Figure 3).

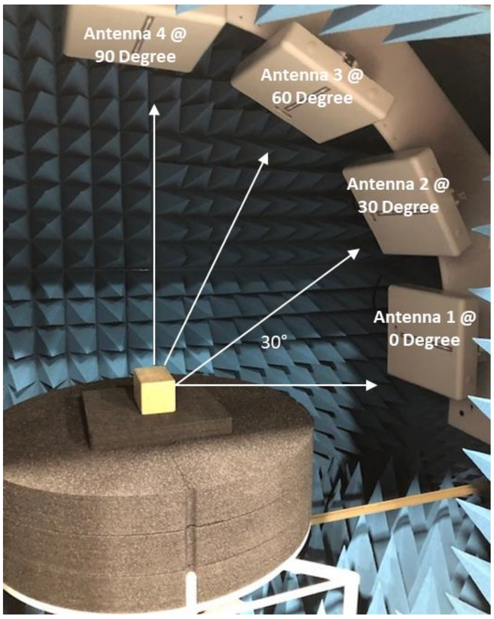

Figure 3. Anechoic chamber with a rotating table and antenna array to test the performance of RFID-tagged products.

To assess the influence of tag orientation, tags were fixed at the top and bottom of each packaging material (Figure 4). To determine the effect of packaging content, bottles were tested empty or filled with de-ionized water. Samples were then placed at the center of the rotating table of the Voyantic chamber facing antenna 1. Tests were done at room temperature (20°C) and repeated three times. Power on tag Forward (PoF) and the Theoretical Read Range (TRR) were selected to assess the RFID tag performance at a fixed frequency of 915MHz. PoF represents the amount of power required by the tag to be successfully activated and read by the reader. TRR represents the maximum distance that a tag can be read using a reader antenna at a fixed power.

Figure 4. Representative samples of polyethylene terephthalate (PET), clear glass, and TETRAPAK® empty bottles (left to right) tagged with Tag 1 on top and bottom positions.

2. Results and discussion

Table 1 shows the results of the Power on tag Forward and Table 2 represents the Theoretical Read Range of different tags influenced by tag positioning and the packaging content when they are empty or filled with water.

Power on tag Forward indicates how sensitive is the tag to be successfully activated and read by the reader. The lower the PoF, the better sensitivity of the tag. Theoretical Read Range is a function of PoF and represents how far away a tag can be read in reference to the reader. These are two parameters to describe the tag sensitivity and performance. The lower the PoF, the better the tag will be. The higher TRR, the better the tag will be.

Table 1. Influence of tag positioning (top or bottom) and packaging content (empty or water) on Power on tag Forward using three tags (Tag 1, Tag 2, Tag 3) on three packaging materials

Power on tag Forward (dBm)	**PET**		**Glass**		**Tetrapak**	
	Empty	Water-filled	Empty	Water-filled	Empty	Water-filled
Tag 1 on Top	-21	ND	-17.3	-3.0	ND	ND
Tag 1 on Bottom	-21	ND	-15.2	4.4	ND	ND
Tag 2 on Top	-5.2	3.8	-2.1	-0.2	2.7	3.0
Tag 2 on Bottom	-4,7	ND	-3.9	-0.4	5.0	4.7
Tag 3 on Top	-1.5	-4.5	2.3	1.5	-4.8	-4.5
Tag 3 on Bottom	-0.7	0.2	-0.1	0.4	-0.7	-1,2

Table 2. Influence of tag positioning (top or bottom) and packaging content (empty or water) on Theoretical Read Range using three tags (Tag 1, Tag 2, Tag 3) on three packaging materials

Theoretical Read Range (m)	**PET**		**Glass**		**Tetrapak**	
	Empty	Water-filled	Empty	Water-filled	Empty	Water-filled
Tag 1 on Top	16.8	ND	10.8	2.1	ND	ND
Tag 1 on Bottom	16.8	ND	8.6	1.0	ND	ND
Tag 2 on Top	3.0	1.0	2.1	1.5	1.0	1.1
Tag 2 on Bottom	2.8	ND	2.3	1.5	0.8	0.8
Tag 3 on Top	2.0	2.7	1.1	1.2	2.8	2.8
Tag 3 on Bottom	1.7	1.4	1.4	1.4	1.7	1.9

From the results of Tables 1 and 2, it is possible to see that changing the tag positioning and filling the bottles with water changes the tag performance in terms of PoF and TRR.

Considering Tag 1, changing the place of Tag 1 from the top to the bottom of the bottle did not affect the readability when bottles were empty. While filling the bottle with water caused performance losses in both cases. In this case, placing the tag on top of the bottle increased the readability. Water interferes with the RF reflection, and as the tag is closer to the free headspace, the better the performance will be. This tag could not be detected at 915MHz in the presence of water. Due to these results, further tests were conducted by positioning the tag close to the bottleneck of the bottles. Additionally, Tag 1 was found not to be readable when attached to the Tetrapak® bottle. This is due to the presence of a thin metallic layer in the poly laminate material which makes this tag undetectable.

Regarding Tag 2, similar to Tag 1, water decreased the readability when compared with the empty bottles. This tag was detectable when attached to the Tetrapak® bottle, however higher energy was required with respect to the PET and glass bottles when Tag 2 was placed on top of the bottles (2.7 dBm for Tetrapak®, -2.1dBm for glass, and -5.2 dBm for PET). Tag 2 was not readable when attached at the bottom of the water-filled PET bottle. This required higher energy when tested on PET and Tetrapak® with low read ranges. Based on this, Tag 2 should be placed on top of all three packaging materials.

Overall Tag 3 had the best results when compared to Tag 1 and Tag 2. Tag 3 performed the best when it was attached to the top of the Tetrapak® bottle. Water filling did not affect the performance of this tag and it was detectable on all packaging materials when filled with water.

While several studies highlight the importance of sensor-based smart packaging for food applications (Zuo et al., 2022), there are limited academic reports that evaluated the impact of food composition and tag placement on the performance of UHF RFID tags. The results obtained from this study were found to be in accordance with the limited research available on this topic, in particular, the effect that water has on tags' performances. Björninen and team in 2011 designed a cheap and compact UHF RFID tag that resulted to be stable in presence of liquid (Björninen et al., 2011). Barge et al. (2017) investigated the effect of temperature and positioning on UHF RFID tag readability for beverage packaging. For what concerns the bottle labeling, when the tag was applied to an empty flask, the power that was needed to be successfully activated and read was very low. The authors concluded that an improper tag positioning can cause a readability worsening effect, leading to complete tag undetectability. Liu et al. (2018) designed a specific UHF RFID tag for liquid products filled in glass bottles, and they investigated its reduction in readability due to the presence of the liquid. The reading ranges of the proposed tag were measured both for the empty and filled glass bottles. Six liquid products were tested, each of which caused a reduction in the reading range in a restricted range. Barge et al. (2019) reported that the RFID tags' reading range is highly influenced by tag orientation with respect to the antenna, as well as by the food products' chemical composition.

Read Range is a function of the energy required to activate the tag, the so-called Power on tag Forward. To confirm this correlation, the PoF results from this study were plotted against the TRR. Figure 5 shows the correlation between the Power on tag Forward and the Theoretical Read Range at 915 MHz for all conditions tested in this study. The results show a strong correlation with the coefficient of determination of R^2=0.9945.

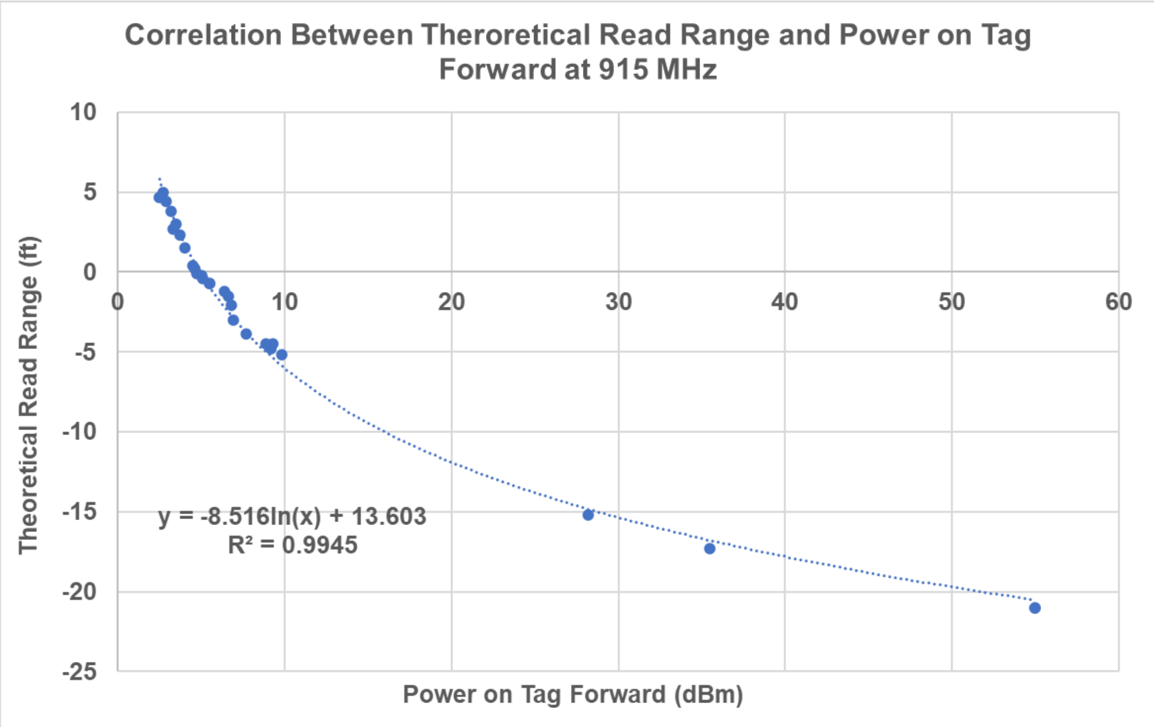

Figure 5. Correlation between Power on Tag Forward and Theoretical Read Range for the values achieved from different tests at 915 MHz.

The results of this correlation could be used to estimate the Read Range zone once the Power on tag Forward of a specific UHF RFID tag is known. This could help the appropriate installation of the RFID readers across the RFID-enables facility.

3. Conclusions

Smart packaging and RFID technology have been widely used in different sectors. The application of UHF RFID tags for food packaging is challenged by the sensitivity to the presence of dielectric materials. To the best of our knowledge, the scientific reports that investigated the correlation between material property and UHF RFID tag performance are not comprehensive. To fill the gap, the overall work aimed to identify and understand the effect of the surrounding environment on the tag's performance. In this work, three commercial tags were tested on bottles made of three different packaging materials including PET, Tetrapak®, and transparent glass. The samples were filled with water to investigate the effect of water on tag readability. The tags' readability (Power on tag Forward and Theoretical Read Range) was assessed within the Voyantic® anechoic chamber using the Voyantic® TagFormance software. Each tag was found to be affected by the presence of water with changes associated with the placement of the tags (top to bottom) and type of the packaging. All the tested tags required different quantities of power to be successfully activated and read as a function of the substrate material they were attached to. Additionally, a general worsening effect on readability was recorded in presence of any of the aqueous solutions. Tag 1 was not designed to work in presence of metals, while Tags 2 and Tags 3 were chosen because of that specific ability. Tag 3 was found to be the best-performing tag among the ones tested, and the top positioning resulted to be the most appropriate placement. The results of this research will be used for the next phase to determine the effect of beverages (e.g., orange juice, apple juice, wine, and milk) on the tag performance. The effect of the surrounding environment on the tags' performances is not the only challenge that has to be solved before UHF RFID tags adoption on a large scale. To widespread the application of UHF RFID technology there is a need to solve its criticisms including cost and low performance in different environments. It is known that the integration of RFID in food packaging would allow traceability, ensuring food safety, but the way the tags interfere with each other and with the surrounding environment must be studied. A deeper investigation would help manufacturers in finding tags that can be universally applied. Further studies are needed to determine the correlation between food composition and tag performance. Finding a physical property that predicts the tag performance losses would facilitate the UHF RFID tag adoption process for food packaging. This will result in better traceability and improved safety.

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