Gain Uncertainty in Commercial UHF RFID Fixed Reader Antennas and Its Effect on Tag Read Accuracy

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Abstract: ***Ultra High Frequency (UHF) Radio Frequency Identification (RFID) is a type of RFID technology that is being widely used in recent days. The fixed UHF RFID readers use tuned antennas for far-field power transmission. The gain specified in the reader antennas' datasheets are often not accurate and vary between manufacturers. This paper presents an experimental method to analyze the gain uncertainty through the path loss measurements. Four commercially available similar sized fixed UHF RFID reader antennas are chosen for this experimentation. The commercial antennas are also benchmarked using an RFID tag for its read rate, read count and the tag`s return signal strength. The impact on the gain uncertainty in RFID applications is also discussed.***

Keywords: ***UHF RFID; Far-Field; Antenna Gain; Uncertainty.***

I. INTRODUCTION

UHF RFID systems comply with UHF Gen2 standards and are used between 860 and 960 MHz frequencies depending on the region of operation. UHF RFID is generally preferred over Low Frequency (LF) and High Frequency (HF) RFID systems due to its advantages viz., longer read range (up to 12 meters), faster data transfer rate, small sized reader antennas, low-cost passive tags, etc. Two major classifications of frequency ranges are 865-868 MHz and 902-928 MHz which are regulated by ETSI (European Telecommunications Standards Institute) and FCC (Federal Communications Commission) respectively. UHF RFID system includes a transceiver (RFID reader), transponder (RFID tag), reader antenna and a software to control and post-process the data from the reader [1].

Two widely used UHF RFID readers are the hand-held reader and the fixed reader. Hand-held readers are smaller in size and most often the reader antenna and the software are incorporated within the hand-held module. A fixed reader is usually a standalone transceiver module to which antennas are externally plugged in via RF ports. The fixed reader has I/O and network / serial ports to interface with a computer software [2]. Some RFID readers bear an integrated far-field antenna [3]. The inclusion of RF ports in an RFID reader for external antenna connection enables the control over RF energy transmission for an application by simply connecting the desired antenna to achieve the desired RF performance.

UHF RFID fixed reader antennas are broadly classified as near-field/proximity antennas and far-field antennas. Near-field antennas are used to track liquid and metal assets [4] in the proximity region while the far-field antennas are used to track other assets at a longer distance. There is a wide range of far-field antennas that are commercially available. The most common way of selecting a far-field antenna is by the antenna gain, VSWR, beam-width, and polarization. RFID systems are mostly installed by the software developers and system integrators who would usually choose a reader antenna by their gain specification. When an antenna model is replaced by another antenna with the similar datasheet specifications, tag read performance difference shall be noticed.

The paper addresses the above-mentioned performance differences by analyzing the gain uncertainties in commercial UHF RFID fixed reader antennas and their impact on RFID tag read accuracy. Research papers like [5] base their research on the commercial antenna's datasheet specifications and it is important to understand the uncertainties associated with their specifications

II. RELATED WORKS

Review of antennas designs such as [6-8] discusses the traditional antenna designs, their disadvantages, and the proposed advantageous design. Reference [9] reviews about recent antenna developments for Cube Sats while the reference [10] reviews on the UHD RFID antennas types and applications. Fixed UHF RFID reader antennas were not reviewed for their gain uncertainties and this is addressed in this paper by testing the commercial antennas against each other.

Most of the gain uncertainty literature is based on the measurement and calibration uncertainties involved while measuring the antennas in a compact anechoic chamber [11-12]. Uncertainties for a GHz double-ridged horn antenna is estimated in reference [13] at 4.8 – 11 GHz frequency range. In this paper, gain uncertainty is analyzed in the UHF range. Gain measurement and uncertainties are assessed in 1575.42 MHz GPS receiving antenna [14]. Fixed UHF RFID readers are monostatic meaning they can have one antenna for both transmission and reception. This paper discusses the gain uncertainty in a transmitting and receiving monostatic antenna that operates in 902-925 MHz frequency range unlike the antenna in reference [14]. The following sections describe the commercial fixed UHF RFID reader antennas used for this experimentation, their datasheet specifications, the measurement uncertainties observed by comparing against themselves and by performing an RFID tag test.

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III. COMMERCIAL UHF RFID READER ANTENNAS

Commercial UHF RFID reader antennas are usually planar and low-profile due to the directionality requirement (directional radiation) and ease of installation in RFID applications. Most common planar antennas are patches antennas. Other directional planar antennas are made from loops, slots, dipole antennas with a ground plane reflector. In this paper four types of commercial planar antennas are chosen from different manufacturers viz., Alien technology's A0501, Laird technology's S9025PR, Laird technology's PEL90206 and Times-7's A5020 (Fig.1) for uncertainty measurements. All four antennas are similar in size (around 5 x 5-inch square) and are planar in nature. Smaller sized antennas are preferred by the RFID industry and thus these antenna types are chosen for comparison.

Table I shows the comparison of specifications according to the respective antenna datasheets [15-18]. It is unclear whether the gain specified in the datasheet is the peak gain or the average gain in FCC RFID frequencies (902 – 928 MHz). In RFID applications, the circularly polarized gain is specified in dBiC which is simply dBi (linear gain of the antenna) + 3 dB with a 0dB axial ratio [19].

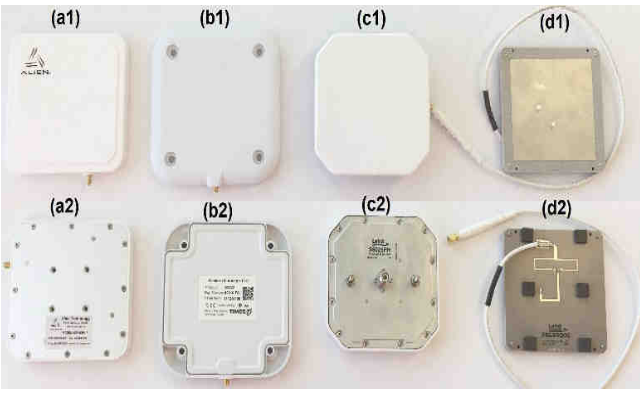

Fig. 1.Commercial UHF RFID reader antennas – a1: Alien 0501 front face, a2: Alien 0501 rear face; b1: Times-7 A5020 front face, b2: Times-7 rear face; c1: Laird S9025PR front face, c2: Laird S9025PR rear face; d1: Laird PEL90206 front face, d2: Laird PEL90206 rear face.

TABLE I. ANTENNA SPECIFICATIONS AS PER THEIR DATASHEETS

Commercial Antenna Model	Circular Gain	Polarization	Beamwidth	VSWR
Alien A0501	6 dBiC	Right-hand Circular	105°	< 1.3:1
Laird S9025PR	5.5 dBiC	Right-hand Circular	100°	< 1.5:1
Laird PEL90206	6 dBiC	Left-hand Circular	90°	< 1.5:1
Times-7 A5020	5.5 dBiC	Right-hand Circular	115°	< 1.4:1

IV. GAIN UNCERTAINTY MEASUREMENTS

The gain of an antenna can either be measured using one of the four traditional gain determination techniques [20-21] viz., the three-antenna technique, the two-antenna technique, the far-field substitution technique, the insertion loss technique and the near-field substitution technique. These above-mentioned techniques are based on the Friss-transmission formula, given by (1).

$$P_B = P_A G_A G_B \left(\frac{\lambda}{4\pi R}\right)^2 \qquad (1)$$

where P_B is the received power at the receiving antenna 'B' whose gain is G_B, P_A is the power transmitted by the antenna 'A' whose gain is G_A, λ is the wavelength of operation and R is the distance between the two antennas A and B.

In this paper, the gain of these commercial antennas was not measured but their radiated power was compared to each other. The actual gain of these antennas can be found by comparing a reference antenna's path loss measurements whose gain is known [20]. Antennas Under Tests (AUTs) are measured for their path losses between themselves and a receiving antenna [20]. Path loss measurements are made in an anechoic chamber for different AUTs using a TR1300/1 vector network analyzer (VNA). TR1300/1 is a 2-port, 1-path VNA where the AUT is connected to port 1 and the receiving antenna is connected to port 2. VNA`s ports are calibrated using a standard calibration kit. Path losses (S_{21}) are measured and compared against each other to find the gain uncertainty. This method is similar to the insertion loss method mentioned in the reference [20] except for finding the actual gain of AUTs by comparing the power measurements against a known reference antenna.

To measure the PEL90206 antenna's path loss, a left hand circularly polarized receiving antenna is required while the other antennas would need a right hand circularly polarized receiving antenna. To avoid the uncertainties involved in using two receiving antennas (LHCP and RHCP), a single linearly polarized receiving antenna is chosen for measurements. The distance of separation between the receiving antenna and the AUT is 1000mm. This distance is much greater than the minimum Fraunhofer distance (d) required to realize the radiating far-field. Equation (2) is based on the largest antenna's dimension (D) i.e., 150mm and its operating wavelength (λ).

$$d = \frac{2D^2}{\lambda} \qquad (2)$$

To capture the circularly polarized fields, the receiving antenna is rotated to measure the power transmitted by the AUT in four different orientations viz., +45° slant, horizontal, -45° slant and vertical (Fig.2). S_{21} measurements are made for a span of 200 MHz with 900 MHz being the center. The frequency of interest (902 – 928 MHz) is highlighted and markers are plotted on the center frequency (f_c) at 915 MHz (Fig.3).

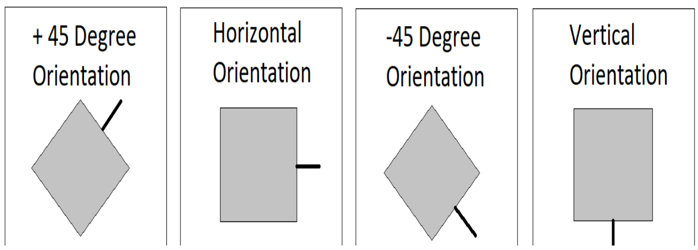

Fig. 2.Receiving Antenna's Orientation To Measure The Circularly Polarised Test Antennas

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Table II lists the S_{21} path loss measurements for low (902 MHz), mid (915 MHz) and high (928 MHz) frequencies. The path loss values for different antennas are different in different orientations and in different frequencies. The A0501 antenna's power distribution is relatively even across the FCC RFID frequency range in all four orientations. The A5020 and the PEL90206 antennas have a narrower response with the peak centered at f_c. The response at the edge of the band is drooping and thus their power is slightly less compared to their peak in both antennas. The S9025PR antenna's response is neither wide nor narrow. The S9025PR antenna's power distribution is maximum at the high end of the band (928 MHz) while the minimum is at the low end of the band (902 MHz).

As mentioned in section III, it is unclear in the antenna's datasheet specifications that the gain specified is the peak gain or the average gain. Thus, all four antennas' peak path loss and average path loss are tabulated in 'Table III'. The peak path loss is the maximum path loss of the antenna observed in any frequency and in any antenna orientation. The average path loss is the average of all path loss values for an antenna in all four orientations and in all frequencies (low, mid and high). It is noted that the A5020 antenna has the highest peak path loss among the other antennas at f_c in +45° slant orientation. The A0501's average path loss is the highest among the other three antennas.

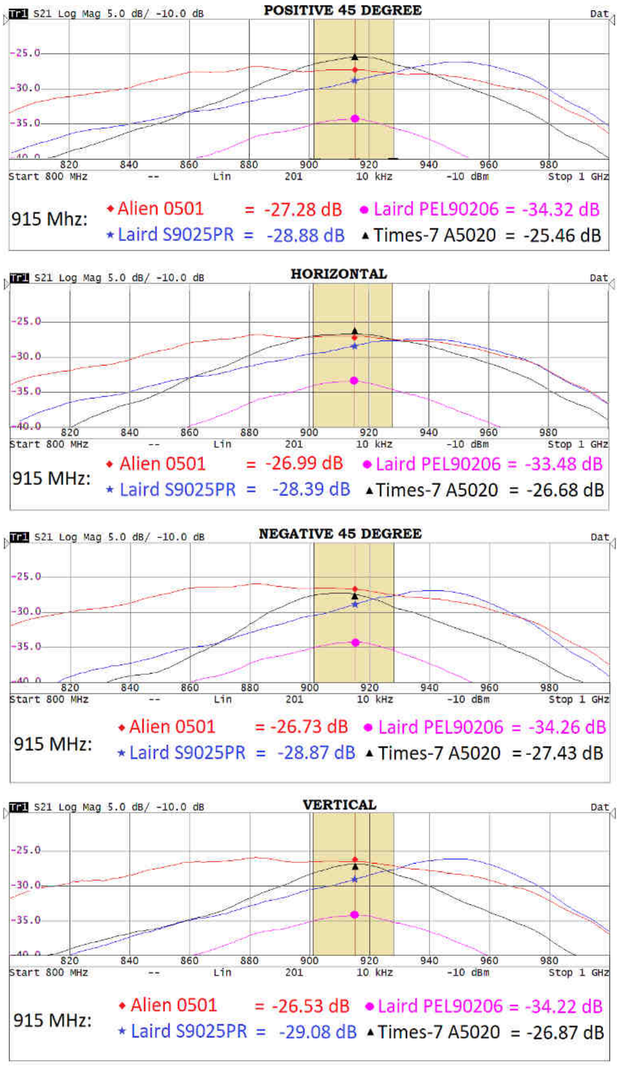

Fig. 3.Path loss measured by the receiving antenna at VNA's Port-2 (S_{21}) for the commercial RFID antennas

Gain uncertainty (based on the *peak path loss* measurements) noted is as follows;

1. The 5.5 dBiC A5020 antenna has 1.07 dB more gain compared to a 6 dBiC A0501 antenna.
2. The 5.5 dBiC A5020 antenna has 8.76 dB more gain compared to a 6 dBiC PEL90206 antenna.
3. The A0501 antenna and the PEL90206 antennas are 6 dBiC rated but the A0501 antenna's peak gain is 7.69 dB more than the PEL90206 antenna's peak gain.
4. The S9025PR antenna's peak gain is 2.2 dB less than that of the A5020 antenna, though both antennas are 5.5 dBiC rated.

Gain uncertainty (based on the *average path loss* measurements) noted is as follows;

1. The 5.5 dBiC A5020 antenna has 0.14 dB less average gain compared to a 6 dBiC A0501 antenna. When the antenna's gain is compared against each other in accordance with far-field substitution method [20], it is inconclusive whether the A0501 antenna's gain is 5.64 dBiC or the A5020 antenna's gain is 5.86 dBiC.
2. Average Gain of the 5.5 dBiC A5020 antenna is 7.45 dB more than the 6 dBiC PEL90206. A5020 antenna's gain cannot be 12.95 dBiC as it is theoretically impossible for a 150 mm x 150 mm sized antenna operating at 915 MHz frequency.
3. The A0501 antenna and the PEL90206 antennas are 6 dBiC rated but their average gain has a discrepancy of 7.59 dB between each other.
4. The 5.5 dBiC rated A5020 antenna and the S9025PR antenna has a difference of 1.62 dB which leads to an uncertainty whether the A5020 antenna is 7.12 dBiC or the S9025PR antenna is 3.88 dBiC rated.

TABLE II. PATH LOSS MEASUREMENTS

Commercial Antenna Model	Antenna Orientation	S_{21} at 902 MHz (dB)	S_{21} at 915 MHz (dB)	S_{21} at 928 MHz (dB)
Alien A0501	+45°	-27.48	-27.28	-27.83
	Horizontal	-27.10	-26.99	-27.47
	-45°	-26.56	-26.73	-27.53
	Vertical	-26.53	-26.53	-27.16
Laird S9025PR	+45°	-30.03	-28.88	-27.70
	Horizontal	-29.47	-28.39	-27.71
	-45°	-30.38	-28.87	-27.66
	Vertical	-30.40	-29.08	-27.69
Laird PEL90206	+45°	-34.99	-34.32	-35.61
	Horizontal	-34.00	-33.48	-34.68
	-45°	-35.03	-34.26	-35.49
	Vertical	-34.93	-34.22	-35.18
Times-7 A5020	+45°	-26.42	-25.46	-26.43
	Horizontal	-26.91	-26.68	-27.49
	-45°	-27.52	-27.43	-29.29
	Vertical	-28.07	-26.87	-28.23

TABLE III. PEAK AND AVERAGE PATH LOSS MEASURED

Commercial Antenna Model	Peak Path loss (dB)	Average Path loss (dB)
Alien A0501	-26.53	-27.09
Laird S9025PR	-27.66	-28.85
Laird PEL90206	-34.22	-34.68
Times-7 A5020	-25.46	-27.23

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Reference [22] mentioned that the uncertainty in antenna's gain measurement could also be due to their poor VSWR. Fig.4 shows that the VSWR for all the antennas is less than 1.4 across the FCC frequency band. It is also noted that the VSWR values are in-line with their corresponding datasheet specifications (Table IV).

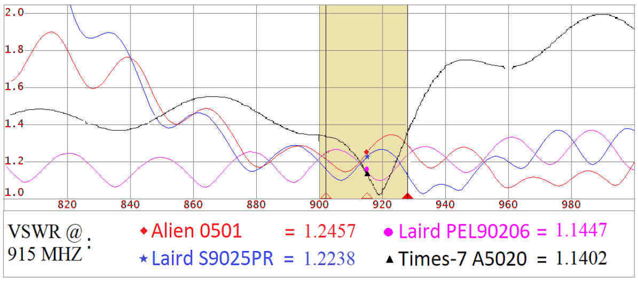

Fig. 4.VSWR measured at VNA's Port-1 for the commercial RFID antennas

TABLE IV. MEASURED VSWR VS SPECIFIED VSWR

Commercial Antenna Model	VSWR at 902 MHz	VSWR at 915 MHz	VSWR at 928 MHz	Datasheet Specs
Alien A0501	1.2119	1.2457	1.2882	< 1.3:1
Laird S9025PR	1.1569	1.2238	1.1251	< 1.5:1
Laird PEL90206	1.2447	1.1447	1.2341	< 1.5:1
Times-7 A5020	1.3325	1.1402	1.3423	< 1.4:1

V. RFID TAG TESTING

Section IV discussed the uncertainty in the gain of different commercial fixed RFID reader antennas by measuring their radiated power. It is found that higher gain specified antennas have lower power transmission while the antennas with low gain specification transmitted at higher power. This uncertainty is further investigated in this section with the help of RFID tag testing. Smartrac's dog bone tag [23] is used for this testing as it is a far-field tag with dipole-like antenna. The tag is 94 mm long and 24 mm wide & consists of Impinj Monza R6 chip. As this is a linearly polarized tag, RFID tag testing involves tests by rotating the tag in four orientations viz., +45° slant, horizontal, -45° slant and vertical. Impinj's Speedway r420 UHF RFID fixed reader [2] is used to test the commercial antennas. The reader is programmed to operate in FCC frequencies (902 – 928 MHz). FHSS (Frequency Hop Spread Spectrum) technique is adopted by FCC which requires frequency hopping between the frequency channels. FCC has 50 channels between 902 MHz and 928 MHz, starting at 902.75 MHz and ending at 927.25 MHz. To cover all the frequency channels, the RFID reader must transmit for at least 60,000 milliseconds [24].

The following are the reader settings used in Impinj multi-reader software on an Impinj Speedway r420 reader to perform a 'Test Run' [24].

A 300 mm RG-58 coaxial cable is used to connect the AUT with the reader. Cable loss for a 300 mm RG-58 cable is ~0.18 dB, which is negligible. The same cable is used to measure all four antennas. The Smartrac's dog bone tag is mounted on a piece of Styrofoam for testing purposes (Fig.5c). Free space tag test is achieved through the Styrofoam block as its dielectric constant of 1.03 [25]. The Styrofoam block is 600 mm long and is placed on the antenna's center to test the antenna's performance at the boresight (Fig. 5a and 5b). The small form-factored fixed UHF RFID reader antennas are often used in RFID applications such as POS (point-of-sale), asset tracking in shelves, etc. These applications will have RFID tags closer to the reader antenna. 600 mm distance is chosen to replicate this scenario and this distance still lies in the far-field region (for all four AUTs).

Run Mode	: Test Run
Start Delay	: 1000 mSec
On Time	: 60,000 mSec
Off Time	: 1000 mSec
Number of Runs	: 1

The test antenna is powered on for 60 milliseconds to read the dog bone tag throughout the time at 10 dBm input power. The tag's read count, read rate and maximum return signal strength indicator (RSSI) are noted. The same test is repeated for different tag orientations and for different antennas as well.

Reader mode : Autoset dense reader
Antenna : 1 (activated)
Tx Power : 10 dBm
Rx Sensitivity : -70 dBm
Search Mode : Dual Target
Session : Session 2

Table V shows the tag test results for all the antennas operated at 10 dBm to read tags in all four orientations. The A5020 antenna has the highest read count in all four tag orientations, followed by the A0501 antenna and the S9025PR. A peak read rate of 39.5 is noted for the A5020 antenna with +45° slant tag orientation while the least read rate of 2.6 is found for the A9025PR antenna in the same +45° slant tag orientation. Tag at +45° slant orientation had the maximum RSSI of -48 dBm for the Times-7 antenna while the minimum RSSI of -54 dBm is noted for the S9025PR antenna in the same +45° slant tag orientation.

At 10 dBm power, the Laird`s PEL90206 antenna did not read the Smartrac's dog bone tag at all in any tag orientation. This shows that the PEL90206 antenna has much lower gain compared to the other antennas. This is in-line with the path loss measurements discussed in Section IV. Based on the read count, read rate and the tag`s RSSI it is vivid that the A5020 antenna has the highest gain followed by the A0501 antenna and the S9025PR antenna. The tag test results for the A5020 and the A0501 antennas would be counter-intuitive when the antennas' average path loss is considered for comparison but would hold true for their peak path losses. The A5020 has 1.07 dB better peak gain in comparison with the A0501 antenna. This is because the RFID reader hops between the frequencies and the A5020 antenna has higher gain compared to the A0501 antenna in frequencies around the f_c (915 MHz). Though the RFID readers are FCC specified, they do not transmit at the edge of the band (at 902.00 and 928.00 MHz).

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The PEL90206 antenna required at least 14 dBm power to read the Smartrac dog bone tag in all orientations (see Table VI). 14 dBm is more than twice as much as the 10 dBm power required by other antennas.

The tag`s maximum RSSI is -59 dBm. This is ~ 9dBm less than the RSSI yielded by the A5020 antenna and ~5 dBm less than the RSSI generated by the S9025PR antenna at 10 dBm input power. From these results, it is conclusive that the PEL90206 antenna`s gain is much lower than the others. For measurement completeness, other antennas are measured at 14 dBm reader power as well. The A5020 had the highest read count, read rate, and RSSI value. It is also noted that the read count and the read rate is not dramatically different between the A5020 and the A0501 antennas at this power level. The A5020`s RSSI is still higher than the A0501 antenna`s RSSI.

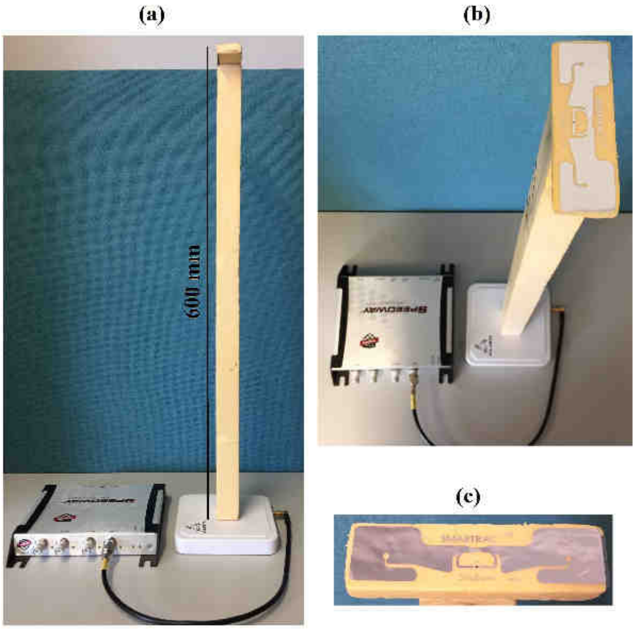

Fig. 5.Setup for RFID tag testing – (a): Alien 0501 antenna connected to an Impinj r420 FCC reader with a test tag on a 600 mm long Styrofoam block; (b) Top view of the setup showing the tag location on the antenna's boresight; (c): Smartrac dogbone wet inlay on a piece of styrofoam.

TABLE V. TAG TEST RESULTS AT 10 DBM READER POWER

Antenna Type	Antenna Orientation	Read Count	Read Rate	Maximum RSSI (dBm)
Alien A0501	+45°	906	15.1	-53
	Horizontal	924	15.4	-53
	-45°	1782	29.7	-51
	Vertical	1177	19.6	-51
Laird S9025PR	+45°	155	2.6	-54
	Horizontal	1128	18.8	-53
	-45°	1027	17.1	-50
	Vertical	590	9.9	-51
Laird PEL90206	+45°	This antenna did not read the Smartrac dog Bone tag at 10 dBm in any tag orientation		
	Horizontal			
	-45°			
	Vertical			
Times-7 A5020	+45°	2370	39.5	-48
	Horizontal	2249	37.5	-49
	-45°	2054	34.3	-50
	Vertical	2292	38.2	-49

TABLE VI. TAG TEST RESULTS AT 14 DBM READER POWER

Antenna Type	Tag Orientation	Read Count	Read Rate	Maximum RSSI (dBm)
Alien A0501	+45°	2651	44.2	-49
	Horizontal	2651	44.2	-48
	-45°	2651	44.2	-48
	Vertical	2648	44.2	-49
Laird S9025PR	+45°	2608	43.5	-48
	Horizontal	2607	44.0	-50
	-45°	2616	43.6	-50
	Vertical	2610	43.5	-48
Laird PEL90206	+45°	665	11.1	-58
	Horizontal	246	4.2	-59
	-45°	583	9.8	-58
	Vertical	778	13.0	-58
Times-7 A5020	+45°	2656	44.2	-46
	Horizontal	2654	44.3	-47
	-45°	2652	44.2	-47
	Vertical	2651	44.2	-46

Long range RFID applications like vehicle tolling, etc., will include longer coaxial cable connection between the antenna and the reader. Longer cables induce power loss. The A5020 antenna would perform better than the other antennas as it can efficiently read tags at low power. For indoor applications like point-of-sale, tag commissioning, etc., all four antennas would perform similar although the input power to the antennas may vary.

Operating the RFID antennas at low power is a key to eliminate stray tag reads. In retail applications, the tagged assets are at the proximity of the antenna and stray tag read is often a problem especially with a half power beam width of ~100° (in both planes). Higher read count and read rate can be achieved by using the A5020 antenna compared to others at low power. Stray tags can as well be filtered in the RFID reader's software by applying the RSSI filtering. Tags reporting at least return signal strength can be ignored as they are located at a farther distance. The Smartrac tag's RSSI values are similar for the A5020 and the A0501 antennas when operated at 14 dBm power. Applying RSSI filters in these two antennas will be efficient compared to the Laird antennas to eliminate the stray tag reads.

VI. CONCLUSION

The gain uncertainty in commercial UHF RFID fixed reader antennas is experimentally investigated by measuring the path loss between the circularly polarized commercial antennas and a receiving linear polarised antenna using a VNA in four different orientations. Power measurement revealed that a lower gain specified antenna (A5020) have high power emission and vice-versa for a higher gain specified antenna (PEL90206). The 6 dBiC gain rated PEL90206 antenna and A0501 antenna has different path-losses. Similarly, the 5.5 dBiC rated A5020 and S9025PR have different path-loss measurements. The RFID tag test results show that the A5020 antenna can read an RFID tag at far-field distances with minimal power and can generate high read counts and read rates whereas the PEL90206 cannot read the tag at all at minimal power.

The return signal strength (RSSI) value from the tag also proves that the gain uncertainty exists in these commercial UHF RFID fixed reader antennas. At higher power, the read count and the read rates are similar for the A5020 and A0501 antennas though there is a 1 dB peak gain and 0.14 dB average gain uncertainty between the same. Tag read counts could be a good indication when choosing an RFID reader antenna. One must select the antenna based on its ability to read the RFID tags rather bu choosing an antenna based on the gain specified in the datasheets.

As part of the future work, the actual gain will be investigated for these commercial antennas through one of the four gain measurement methods. The effect of superstrates has to be tested to simulate practical RFID applications (like mounting the antennas under a wooden desk, mounting the antenna over a ceiling tile, etc). Since the S9025PR antenna`s peak gain is off-tuned at 945 MHz, it will be worth testing the antennas with different superstrates to see the detuning effect and its impact on the RFID tag reads.

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