Fixed UHF RFID Reader Antenna Design for Practical Applications: A Guide for Antenna Engineers With Examples

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***Abstract*—An overview of Ultra High Frequency (UHF) Radio-Frequency Identification (RFID) practical applications and the reader antenna design requirements are presented in this paper. As each application is different and their physical, environmental, electrical, and Radio-Frequency (RF) requirements will also differ, a design methodology is proposed by analyzing all the requirements for a practical reader antenna. Reader antenna performance measures and test procedures are also formulated. As an example, an embeddable reader antenna is designed and fabricated for self-billing kiosk application in a retail environment. The designed antenna is measured in terms of various RF and RFID performance metrics and validated that it meets all the requirements sought by the application.**

***Index Terms*—Reader antennas, UHF RFID, antenna design, conformal, practical, fixed antenna, embedded antenna.**

I. Introduction

Automatic identification and data capture (AIDC) is an emerging technology that identifies objects, capture, and stores the object data directly into a server system without any human intervention. Radio Frequency Identification (RFID) is one of the AIDC technology which is widely used in our day-to-day life. RFID systems can be classified into active or passive system based on the tag's architecture. Tags are passive when they do not require a power supply such as a battery to operate. Active tags consist of a battery and a transceiver built-in. Passive RFID systems are categorized based on their frequency of operation viz., the low frequency (LF) 125–134 kHz, the high frequency (HF) 13.56 MHz and ultra-high frequency (UHF) 860 to 960 MHz passive RFID systems. A typical UHF RFID system consists of an interrogator (also known as the reader), reader antenna, transponder (also called a tag), software (reader firmware, middleware, and the application software), and other accessories such as coaxial cables for antenna connection, data cables, and power cables. The UHF RFID is advantageous over the LF and HF RFID systems because they have a greater tag detection range (more than 8 meters), faster data transfer rate, multiple tag detection (around 200 tags or more at a time) and lower tag costs.

The UHF RFID frequency of operation, the reader to tag communication technique and the maximum allowed effective radiated power (ERP) and the effective isotropic radiated power (EIRP) are region specific and are specified by [1]. The two main frequency bands for UHF RFID are 902–928 MHz and 865–868 MHz. Countries like Canada adopts the full 902–928 MHz bandwidth for communication whereas countries like Israel (915–917 MHz) or Singapore (920–925 MHz) uses part of the 902–928 MHz spectrum for communication. The reader to tag communication technique can either be frequency hopping spread-spectrum (FHSS) or listen-before-talk (LBT) or according to the European telecommunications standards institute (ETSI)-302 208 standards. The communication techniques and the ERP/EIRP power mentioned above are different for different regions.

The reader to tag modulation can either be double-sideband amplitude-shift keying (DSB-ASK), single-sideband amplitude-shift keying (SSB-ASK) or phase-reversal amplitude-shift keying (PR-ASK) modulation types [2]. The reader transmits an unmodulated carrier signal in periods along with a modulated signal where the unmodulated signal is rectified to harvest the energy by the tag. The harvested DC energy powers the chip for data processing and back-scattering. The back-scatter modulation takes place by varying the front-end complex radio frequency (RF) input impedance of the chip [3]. The modulated signal contains the information of the tag/asset that is interpreted by the RFID reader through the software by liaising with the database.

Reader antennas in UHF RFID systems are critical unlike LF and HF RFID where an inductor coil is used for transmission and reception. Inductor coils create near-zone RF fields. The UHF RFID reader antennas can be both far-field and near-field radiators. The antenna's characteristics such as polarization, bandwidth, gain, voltage standing wave ratio (VSWR), beam-width, front-to-back ratio are vital and have a direct impact on the tag detection performance. During a practical UHF RFID system deployment, often reader antennas are not given enough importance compared to other system components such as the readers, tags or the software. Reader antenna installation is usually the final step in an RFID project implementation. The selection criteria for a reader antenna design is much more than the recommendations specified in [4]. It is rather application specific. A generic patch

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antenna or a dipole antenna would not satisfy all the RFID requirements in an application.

II. Literature Survey

There are numerous reviews and surveys on passive UHF RFID tag antennas but are very limited on UHF RFID reader antennas. A generic meandered tag antenna review with an example design is given in [3] while [5] and [6] describes the UHF RFID tag antenna's design issues and measurements. Other surveys such as [7] and [8] are on the RFID reader's anti-collision protocols and the effects of interference sources in a congested RFID environment, respectively. A review on UHF RFID reader antennas by the authors in [9] is just an overview of different types of reader antennas viz., fixed reader antenna, desktop integrated reader antenna, hand-held and mobile readers. It did not provide any information towards the reader antenna design requirements and analysis for practical applications. Reference [10] reviewed a UHF RFID reader antenna design based on a zero-phase shift line (ZPSL) loop antenna for near-field radiation. In [10], the authors proposed a UHF RFID reader antenna design based on a ZPSL single loop antenna, a ZPSL dual-loop antenna and a ZPSL grid loop antenna.

Several other reader antenna designs such as [11] and [12] are proposed for general UHF RFID applications. They do not discuss about the RFID challenges faced in different applications but presumed the antennas would work in all scenarios. A printed reader antenna design is proposed by [13] for potential retail applications. Although a retail application would have multiple practical needs, the paper has only identified and addressed two needs viz., a) low-cost manufacturing method and b) survival of RF interference in a metal environment. Similarly, the low-cost antenna design proposed in [14] for hospital applications did not consider the challenges involved in a health care sector other than cost. The antenna designs are fundamental and would not excel in real-world applications.

This paper focusses on various UHF RFID applications, their challenges, and requirements for reader antennas. Based on that, a reader antenna design methodology is proposed, and application-specific antenna measurement techniques are also discussed in this paper. Lastly, a practical application is considered as an example, and the proposed antenna design methodology is applied to obtain a reader antenna design. The antenna design is fabricated and tested for practical RFID performance.

III. Reader Antenna Applications and Challenges

UHF RFID is being adopted by most of the industries viz., the primary sectors (raw materials), the secondary industries (manufacturing and production), the service industries (retail, healthcare, hospitality, transport and so on) and the intellectual service industries (information technology and other knowledge-based services). Fixed readers are preferred over hand-held readers because the use of handheld readers involve human operators and consequently are subject to human errors. The following elaborates common UHF RFID fixed reader antenna applications and their challenges.

A. Point of Sale (PoS) Application

Reader antennas are predominantly installed in point-of-sale counters and self-service kiosks in the retail or hospitality industries. In retail stores, RFID in point-of-sale and self-service kiosks are used for billing and purchasing the goods whereas, in hospitality industries, RFID in help-desk/reception is used for personal identification and services. Fixed UHF RFID enables fast and reliable billing, unlike traditional barcode-based operation [15]. Retail industry varies from small convenience stores to bigger supermarket chains. The point-of-sale counter and the self-service kiosks will not be the same across all the shops, and thus the antenna choice will also differ based on the antenna's physical parameters such as dimensions, antenna's radome material, fastening options, etc.

The assets in a retail store can be metals, high or low-density solids, liquids, frozen items, fabrics and so on. Some of these assets posses' technical challenges in tag readability by the reader antenna. A liquid asset is difficult to be read by a far-field reader antenna as RF gets absorbed by liquids. Similarly, a near-field antenna may not have enough energy to read a stack of high-density solid assets. A far-field antenna operating at high power may find other stationary tags in the proximity leading to stray tag reads. Eliminating the stray reads is key for a robust retail RFID system.

B. Inventory Management

Asset and inventory management in the industry is one of the primary reasons why UHF RFID became more popular as it can detect multiple tagged assets at greater distances at once. Inventory is managed in both front-end (stores, manufacturing plants and offices) and back-end premises (storage warehouses, procurement and delivery areas, disposal and recycling stations). Assets can either be stored in free form (in bins or tubs) or can be boxed (cardboard or plastic containers) in a back-end store. They may be arranged on racks or be palletized. Each asset can have a dedicated tag, and they can be grouped in a box to bear a master tag. The number of tags per shelf or pallet is humongous, and this becomes a challenge in reliable inventory management. In addition, a densely palletized asset may encounter the risk of tags not being read in the center of the package. A high gain antenna without breaching the power regulations is necessary to achieve the intended performance. Metal shelves and racks are not transparent for the RF fields, and thus multiple reader antenna deployments per shelf are essential. The reader antenna's cost is an essential factor as tens and hundreds of them will have to be deployed. The reader antenna needs to be robust in its performance when it is located near metal shelves or racks.

Assets are segregated in front-end shops and are stored in different locations. In a tool shop, for instance, hand tools, power tools, and air tools are stored in different aisles in the front-end shop. Inventory on these segregated assets is relatively but may face other challenges such as RF field obstruction by humans (customers), false reads due to the environmental reflections and stray reads.

C. Shelving and Cabinetry Applications

Unlike the warehouse shelving asset management mentioned above, high-value assets such as pieces of jewelry, documents, shreds of evidence, museum pieces and artifacts require real-time inventory management. The RFID read accuracy has to be 100% as the industry cannot afford to lose any single asset. In addition to the read accuracy, the location information of the assets is vital as well. Localization of the assets can be achieved by grouping them in two different ways viz., a) shelf-based within the entire cabinetry b) sector-based within each shelf. This localization can only be achieved by deploying a dedicated reader antenna per shelf, that fills the RF energy in that shelf alone or multiple reader antennas within a shelf, with controlled radiation. The former requires an antenna whose beam is controlled and would not spill over to the other shelves and the latter requires an antenna with limited surface dead zones and little to no back radiation for consistent retrieval of the information on assets' location.

D. Portal Applications

A portal refers to a gateway where RFID reader antennas are deployed to track assets that traverse through. A portal can be an industrial portal, a retail portal or a door-way portal. Industrial portals can be as wide as a dock-door in a warehouse loading dock [16]. Heavy-duty trucks, forklifts, and vans travel through the industrial portal. The reader antenna's physical robustness to handle impacts and the ability to read tags accurately in a highly dense and RF reflective environment is a challenge. Retail portal, on the other hand, has different types of challenges viz., elimination of stray tag reads, the ability to read densely packed assets, antenna's aesthetics and so on. Personnel tracking in small offices using a door-way portal has challenges associated with the human body attenuation. The human body absorbs the radio waves, and thus reliability in personnel tracking is affected. Door-way reader antennas must be aesthetically appealing and seamlessly installed to avoid any safety risks. Most common doorway frames are 80 to 100 mm wide, where a 10-inch square antenna becomes a safety hazard when installed without protection.

E. Race-Timing Applications

One of the most common applications of UHF RFID is race-timing. UHF RFID is preferred because of its ability to detect tags faster and at farther distances. Outdoor race timing events required water-resistant reader antennas to handle harsh environments. A race timing reader antenna can be installed overhead or pole mount on the sides or on the floor at the finish line [17]. Tags are located on the runners' bibs or shoes and cyclists bear tags on their helmets or their bikes [18]. Installing ground antennas involves less infrastructure. A higher read accuracy can be achieved as the antennas are close to the tags (in the case of shoe or bike tags). Conversely, a rugged ground antenna is a requirement to handle the wear and tear caused by the runners and cyclists. The antenna may also have to withstand dirt, rain, varied ambient temperature and humidity, and other environmental impacts. When longer array antennas are installed on the ground to cover a larger finish line with less number of antennas, the antenna array must have an even power distribution along the length of the array at different heights to avoid dead zones. This is a challenge as array antennas tend to have maximum power in its center and droops in the edges.

F. Conveyor Applications

Industry automation, airport baggage handling systems, supermarket checkout areas and many other industries rely on conveyors and are interested in tracking the assets that travel through those conveyors. Reader antennas can either be mounted over the conveyors (on top or on the sides) or under the conveyor belt to detect the tagged assets [19]. The under-belt approach is practical as it is seamless and requires less infrastructure. The collision of assets traveling on the conveyor with the reader antennas can also be prevented. The size of the reader antenna is critical when installing under the conveyor belt. The antenna has to match the belt's width to have an even power distribution across the width and accurately track the assets traveling in the edge of the conveyor belt. The antenna's radome must be sufficiently strong to handle extreme wear and tear and offer low friction. The conveyor antennas must have a confined beam to avoid detecting unwanted assets in the near-by area. For instance, the reader antennas installed in an airport check-in area should not read the tags of baggage that are in the proximity of the intended passengers who are checking-in.

G. Pharmaceutical and Medical Applications

Asset tracking management in the pharmaceutical and medical industries are highly critical due to the nature of the products. Pharma assets can range from vaccines, drugs, and steroids, which requires a controlled temperature environment for storage and transportation [20]. Reader antennas installed in the fridges and freezers must be able to operate at extremely low temperatures for real-time asset management. The antennas may have to withstand condensation if there is any change in temperature and humidity. Medical industries can be broadly classified into medical devices or instruments manufacturers and users, such as hospitals and clinics. Medical instruments such as surgical instruments, cannula and so on require regular monitoring for autoclaving, sterilization and maintenance. The instruments will be monitored throughout this cleaning process and the reader antenna must meet the medical compliances. UHF RFID is also used in hospitals for general asset tracking and patient monitoring applications. Low-profile conformal reader antennas are health and safety compliant, preventing patients from bumping into the antennas. Chemically resistant radomes are necessary to guard the antennas against the cleaning reagents used in hospitals.

H. Vehicle-Tolling and Vehicular Applications

Passive UHF RFID gains interest in vehicle tolling applications where the reader antennas are installed in toll gates, checkpoints and car parks barricades. As the antennas are permanently installed outdoors, they will have to withstand the environmental changes and climates without trading off the performance. Challenges include varied temperature and humidity, long-term exposure to solar and UV radiation, wind, and rain. Powerful antennas are necessary for long distance tag detection. The reader antennas installed in vehicles for mobile asset management such as freight and transport industries require an antenna that can handle vibrations and physical impacts.

IV. Reader Antenna Design Requirements

Each industry is unique, and its UHF RFID requirements are also different. In this section, the UHF RFID reader antenna design requirements are formulated by understanding the applications and their challenges in the previous section. The design requirements are classified into physical, environmental, electrical and RF requirements.

A. Physical Requirements

1) Size: The size of the antenna is a critical factor in a practical reader antenna. Smaller antennas are preferred in space-constrained applications whereas larger array antennas are necessary for powerful radiation that can read tags at greater distances. Antennas designed for standard dimensions are more attractive in practical implementations than a non-standard design. For example, a 10-12 inch or 300 mm square antenna is preferred for non-destructive installation in shelving applications because the standard depth of a shelf varies from 10 to 12 inches. Standard antenna dimensions enable modular array antenna realization. Low-profile and planar antennas are preferred as they utilize less hardware space [22].

2) Substrate and Radome Material: A practical reader antenna is susceptible to stress, strain, abrasion, and impact. The radome of the antenna is a protective cover that shields the antenna from the above mentioned physical influences. The radome will have to be indestructible and RF compatible. Plastics such as poly-tetra fluoro ethylene (PTFE), acrylonitrile butadiene styrene (ABS), poly-carbonate and fiber-glass are some of the commonly used RF compatible radomes. Radomes made from self-lubricating materials such as nylon, acetal and polyphenylene sulfide (PPS) offer very minimal friction and survive extreme wear and tear [23]. Certain types of planar antennas like microstrip patch antennas have a dielectric substrate as part of the design whose dielectric properties are critical for the antenna's RF performance [24]. Other properties of the substrate such as fire retardancy are also essential to meet the on-site health and safety requirements. Both radome and substrate material has a more significant impact on the antenna's cost. Material's availability, manufacturing techniques, and ease-of-manufacturing are some of the parameters that are directly proportional to the cost.

3) Feeding Mechanism: Planar antennas such as patch antennas can be probe fed using a cable or connector, or excited through strip lines, microstrip lines and co-planar waveguides which are in turn coaxial cable or connector fed. A cable-fed antenna is reliable during practical installations compared to a connector-fed antenna as they do not involve any in-between connection joints while routing the cable to connect with the RFID reader located in a different location. Cable's power losses, impedance and bend radiuses are some of the essential parameters to select a cable. Any damage to the cables in a cable-fed antenna will require replacement of the antenna while it is practical to replace just the cable alone in a connector-fed antenna. Strain relief is necessary for both cabled and connector fed antenna to relieve the mechanical stress and protect them. Strain relieves are often incorporated within the antenna structure or with the housing (radome).

4) Fastening or Mounting: Practical antenna deployment requires ease of mounting or fastening the antenna into existing structures such as walls, desktop, cabinets, shelves or on masts and poles. The planar flat panel antennas can have corner holes for mounting the antenna flush against one of the structures mentioned above. The antenna's performance will have to be optimized for the interference caused by the metal fastening screws or bolts. Pole or mast mounting is viable using commercial video electronics standards association (VESA) mounting brackets. The planar antennas should bear threaded rear studs that are compatible with the VESA standards. The VESA brackets will have a metal plate with pre-drilled holes through which the antenna's studs slot through. This will then be fastened with washers and nuts. The antenna's performance will have to be optimized for the impact of the bracket's metal plate.

5) Aesthetics: Reader antennas deployed in customer-facing environments like a jewelry shop or a self-service supermarket kiosk requires aesthetically appealing and seamlessly installed antennas. The antennas used in health-care applications needs to be hazard-free and safe. Sharp-edged and protruding antennas pose serious safety risks in hospitals and clinics. The location of the cable or the connector's exit plays a vital role in the elegant installation. The cable routing can be hidden and made invisible with a rear connector or cabled antenna.

B. Environmental Requirements

1) Temperature: The storage and operating temperatures are the two essential temperature specifications that are essential for a practical reader antenna. Temperature changes affect the antenna's resonance, return loss and radiation parameters [25]. Antennas should not deform or get damaged internally when stored in warehouses or containers due to changing weather and different daytime or nighttime temperatures. Materials insusceptible to change in temperatures are required for designing a reader antenna. Operating temperatures of an antenna are the maximum and minimum temperatures at which the antenna can function effectively without deviating from its specifications significantly. Passive elements such as resistors, capacitors or any other components such as adhesives used as part of the antenna design are required to meet the operating temperature specifications. Antennas installed in pharmaceutical fridges and freezers have the requirement for low-temperature operation.

The international electrotechnical commission (IEC) prepares and publishes the international standards for electrical and electronic related equipment. The IEC 60068-2-1 and IEC 60068-2-2 are the low and high-temperature standards used to assess the antenna's ability to perform under extreme cold and dry heat environmental conditions [26]. Tests are performed in controlled test chambers for up to 72 hours.

TABLE I
INGRESS PROTECTION CODES

1st Digit	Dust Protection level	2nd Digit	Water Protection level
0	Not protected	0	Not protected
1	Protected against 50 mm diameter solids	1	Protected against vertically falling water drops
2	Protected against 12.5 mm diameter solids and greater	2	15° tilted equipment protected against vertically falling water drops
3	Protected against 2.5 mm diameter solids and greater	3	Protected against water spray at any angle up to 60°
4	Protected against 1 mm diameter solids and greater	4	Protected against splashing water in any direction
5	Dust protected to some degree. Equipment's operation is unimpaired.	5	Protected against a 6.3mm nozzle water jet in any direction with
6	Dust tight. No ingress at all.	6	Protected against 12.5 mm water jet in any direction
		7	Equipment is immersed up to 1m water depth.
		8	Equipment is immersed up to 3m water depth

TABLE II
ADDITIONAL AND SUPPLEMENTARY LETTERS

1st	Dust Protection level	2nd	Water Protection level
A	Protected against hand	f	Protection against oil ingress
B	Protected against finger	H	For high voltage equipment
C	Protected against a tool	M	Water test on the moving parts when in motion
D	Protected against a wire	S	Water test on the moving parts when they are stationary
		W	Protected for specified weather conditions

2) Humidity: Humidity is a measure of the presence of water vapor in the atmosphere and has an impact on the antenna's performance [27]. Reader antennas installed in environments where the atmospheric humidity is not controlled will have detrimental effects inaccurate tag detection. Moreover, condensation occurs when the temperature changes along with the humidity. The dew or the water droplets inside an antenna considerably influence the antenna's performance. Thus, robust antenna design is required to adopt the change in humidity. The antenna design should be in accordance with the specification prescribed by ETSI EN300019-2-4 to comply with the effect of humidity [28]. Humidity tests are performed in a controlled humidity chamber at a 95% relative humidity for at least 150 hours. Condensation in an antenna can be eliminated by ingress protecting the antenna, which is discussed in the following section.

3) Ingress Protection: The dust and water resistance need for a practical reader antenna enables the antenna to outlast in various indoor and outdoor applications. IP rating defined by IEC 60529 [29], classifies the degree of solid (dust) and liquid (water) ingress protection. The IP code is a two to a four-digit code where the first and second numeral corresponds to the product's level of protection against dust and water, respectively (refer to Table I). The third and fourth letters are optional, and they are termed as the additional and supplementary letters (refer to Table II).

Almost all the industries require reader antennas to be IP rated to some extent. Monolithic printed antenna design can be IP rated without a radome. Antenna's IP rating is otherwise enabled by the radome's design A higher IP rating is achieved by using rubber gaskets or flexible silicone-based gaskets with the antenna's radome. Dust and water tightness around the connector or the cable is achieved by using O-ring and grommet gaskets. In a connector-fed antenna, the extension cable that connects the reader and the antenna is also required to be IP rated. It is important to perform both water jet and immersion testing as the physical pressure handled by the antenna will be different for both the cases. A typical outdoor antenna is IP65 and IP67 rated.

4) Vibration and Impact Resistance: Reader antennas installed in vehicles such as trucks and vans undergo a range of vibration and impacts. Vibrations can cause disconnects within the antenna's architecture and may lead to malfunctioning. For instance, a disconnected antenna feed may change the antenna's input impedance leading to a poor Voltage Standing Wave Ratio (VSWR). Other physical structures such as the screws holding the antenna's radome intact are also vulnerable to the effects of vibration. This creates the vibrational resistant requirements for the reader antennas. A monolithic patch antenna design is less prone to damage compared to suspended patch antennas over air dielectric. Screws can be replaced with industrial adhesives to sandwich the layers of the antennas. Pressure sensitive adhesives have a greater vibration resistance due to its vibration damping properties [30]. Antenna radome can also be adhered to the antenna making the whole construction solid-state.

Impact or shock, on the other hand, are more prominent in industrial applications. Automated robotic arms, conveyor systems, and forklift operated warehouses are some of the applications where the reader antennas may experience physical impacts. A solid-state antenna with a hard radome can overcome these impacts. The IEC 60721-3-4 standard elaborates on the test requirements for both vibration and shock resistance [31]. Vibrational tests can either be sinusoidal or random. In sinusoidal vibration, the vibration frequency, displacement, and acceleration are specified for different axes and the test is performed for 3-5 sweep cycles. In random vibration tests, the test is carried on a defined frequency for a duration of 30 minutes in various axes. For shocks, the shock spectrum duration, acceleration, number of bumps and the direction of bumps are defined.

5) Solar Radiation: Permanently installed outdoor antennas are scorched by the sun especially in regions closer to the equator. The ultra-violet-A (UV-A) light is not absorbed by the earth's ozone layer. Certain types of plastic radomes cannot handle long-term UV-A solar exposure and can become brittle. A brittle outdoor antenna has a greater chance for dust or water ingress through the cracks. The internal antenna's performance is impaired when the ingress protection is compromised. UV inhibitor additives can be added to plastic radomes during the

TABLE III
TYPES OF UL-94 FLAMMABILITY RATINGS

Type	Specimen Orientation	Extinguishing time	Test outcomes
5VA	Vertical	Within 60 seconds	Drips not allowed. Plaque specimen may not develop hole
5VB.	Vertical	Within 60 seconds	Drips not allowed. Plaque specimen may develop hole
V-0	Vertical	Within 10 seconds	Non-inflamed particles drips allowed
V-1	Vertical	Within 30 seconds	Non-inflamed particles drips allowed
V-2	Vertical	Within 30 seconds	Drips of flaming particles allowed
HB	Horizontal	<76mm/min burning of <3mm thick specimen or burning stops before 100mm	

process of injection molding. The long-term solar radiation test can be accelerated in a laboratory by using different light sources for different testing scenarios. Different exposure conditions can be simulated by using different UV lamps with corresponding irradiance levels, temperature, and light exposure timing. The ASTM G154 test standard describes the standards for accelerated weathering [32].

6) Flammability: Indoor reader antennas need to comply with the building's fire and flammability requirements. When the antenna's substrate and radome are made from plastic, they must comply with the safety standards prescribed by the Underwriters Laboratory (UL) [33]. The UL-94 standard determines the plastic's propensity to either spread the flame or extinguish when subject to ignition. A 127 x 127 mm^2 sample is burnt to find out applicable flame-retardancy rating according to Table III.

7) Salt Mist: Outdoor reader antennas can corrode over time, especially those which are deployed in coastal regions. Corroded antenna parts such as the antenna's ground plane or the radiator can have adverse effects on the antenna's overall performance. The corroded antenna can also break over time leaving the antenna unusable and need to be replaced. Corrosion can be avoided by using highly corrosive-resistant metals or treating the metals through galvanization or anodization. The Salt mist test is defined by IEC 60068-2-11 standard [34]. The test is carried out in an enclosed chamber at a temperature of 35°C by a continuous indirect spray of salt water solution with a pH between 6.5 and 7.2. The salt water's spray rate is between 1.0 and 2.0 ml/80cm^2 per hour.

8) Wind Survival: Reader antennas mounted in masts for applications such as vehicle tolling is susceptible to the effects of winds. Antennas with the large surface area will be pushed away by the wind compared to smaller ones. Planar antennas such as patch antennas are less affected by the wind as a radome often encloses them. Antennas like Yagi-Uda and log periodic consists of metal elements at fixed locations in relation to the operating wavelengths. When the position of these elements is disturbed by the force of the wind, the antenna's characteristics such as resonant frequency, radiation pattern, impedance matching, antenna gain are greatly altered. Heavy-duty mounting studs are also required to mount the antennas safely and will not pose any health and safety hazard. Wind load tests are specified by ANSI/TIA-222-G [35] and EN 1991-1-4 [36] in the USA region and Europe regions, respectively. The impact of wind speed and wind direction on antenna loading is tested by the wind tunnel tests viz., constant speed yaw sweeps and velocity sweeps, also known as the Reynolds number sweeps. During the constant speed yaw sweep, the wind load is measured in different yaw angles at incremental 10 or 5 degrees from 0° to 180° at a constant wind speed of 150 km/h. The speed of the wind is varied from 40 to 180 km/h during the velocity sweep tests.

C. Electrical Requirements

1) Antenna Detection Circuitry: The readers use two different antenna detection methods to ensure that an antenna is connected before the reader can start to transmit the energy through its RF ports. An open-circuited RF port offers maximum power reflection due to impedance mismatch that would damage the reader. When the port impedance is matched by connecting an antenna (load), the reflected power is minimized. Some RFID readers like Impinj Speedway r420 measures the reflected RF power in terms of VSWR to make sure that an antenna is connected to its RF ports. Other readers like the JADEK's Thing-Magic M6e senses for a DC resistance across the center pin and the ground of the RF ports. The DC resistance that the reader's algorithm is sensing is between 50 Ω and 10 kΩ [37]. For a reader antenna to be compatible with all the RFID readers in the market, the antenna must have a DC resistance across the center pin and the antenna's ground, and a good VSWR specification. In some other readers, a 0 Ω DC resistance between the input and the ground is also accepted.

2) Electrostatic Discharge (ESD) Protection: Electrostatic charges can be built on the antennas in applications where the assets are constantly moved over the antennas. For instance, in a point-of-sale application, static charges can get built on the antenna's surface when assets are moved over the antennas during billing. A simple event like picking up a common polyethylene bag can generate 20,000 volts of ESD at 20% relative humidity [38]. When the antenna is mounted underneath the counter's conveyor belt, the magnitude of the built static charges will even be greater as the conveyor belt now acts as a Van-de-Graff generator. If the antenna is not earthed properly then the static electricity can damage the RFID readers. Electrostatic charges building in a folded dipole antenna or a traveling-wave antenna is minimal as the ground is referenced to the radiator either directly or through a load resistance. In a patch antenna, the radiating element is isolated from the antenna's ground plane completely. The static charges built on the radiating element may leak through the cable and can damage the reader's transceiver system. If the radiating patch has a low DC resistance path between the radiator and the ground plane, then the electrostatic charges can get discharged through the RFID reader's earth connection. The DC resistance path can be created by having a short-circuiting via between the ground plane and the center of the patch in case of a half-wavelength patch antenna, where the patch antenna's voltage is 0 V theoretically. A quarter-wave short-circuiting stub may also be incorporated as part of the design at the antenna's input which will create a DC short for the ESD.

D. Radio Frequency (RF) Requirements

1) Frequency of Operation: Resonant antennas are tuned for a range of frequencies and are called as the antenna's operating frequency. The antenna's operating frequency must complement with the RFID reader for efficient operation. Reader antennas can either be designed for the two main frequency bands viz., 865 - 868 MHz (ETSI) and 902 - 928 MHZ (FCC) or for a global 865 - 930 MHz frequencies. The FCC and ETSI UHF RFID frequencies are defined in FCC part 15.247 [39] and ETSI EN 302 208 V3.1.0 (2016-02) [40], respectively. Every country has its own regulatory standards for the UHF RFID frequency of operation. They either authorize the whole FCC or ETSI frequency band or a sub-band within those frequencies. For instance, the sub-band 915 - 917 MHz is the authorized frequencies in Israel while Chile is authorized to use the entire 902 - 928 MHz FCC frequency band.

2) Mode of Operation: A resonant antenna typically has two types of operating modes namely near-field and far-field operation [41]. In UHF RFID, the antenna's propagating far-field components are utilized to detect the tags at a greater distance. The near-field components are essential in tag detection at instances where the far-field components are incapable. For example, in liquid asset management, the near-field components are far more efficient than the far-field in tag detection as the far-field components are vulnerable to absorption by the liquids. Thus, the mode of operation is an important design parameter for a reader antenna design. When a reader antenna is designed for near-field operation, a uniform magnetic field distribution on the antenna's surface is vital to eliminate the null zones. Reader antennas have to be specifically designed for the near-field or far-field mode of operation.

3) Polarization: The polarization of the reader antenna refers to the wave's polarization transmitted by the antenna [42]. A vertically polarized tag cannot be detected by a horizontally polarized reader antenna and vice-versa. Thus, the reader antenna's polarization should match the tag antenna for efficient tag detection. The tag's read distance can be significantly affected due to polarization mismatch. A circularly polarized reader antenna can detect tags in any orientation.

Linearly polarized antennas can be used in applications like vehicle tolling where the tags on the vehicles are made to match the reader antenna's polarization and are fixed. In a shelving application, the tagged assets may not always be oriented in the same manner, leading to a mismatch between the reader antenna's and the tag's polarization. This problem can be overcome by using a circularly polarized reader antenna.

4) Gain and Directivity: An antenna's gain is the measure of maximum power transmission in a given direction [42]. An antenna's directivity is the measure of the directionality or the focusing-ability of its radiation [42]. The antenna's gain and directivity are essential parameters for reader antennas. They enable long-distance tag detection ability. A patch antenna is a type of low-profile planar directional antenna whose gain and directivity are dependent on the size of the ground plane, substrate's dielectric constant, loss tangent and the number of patches. A slot or a dipole antenna over a ground plane can also produce directional radiation. Their gain is also dependent on the factors like the size of the ground plane and the substrate's characteristics and the number of radiators, mentioned above. Other non-planar directional antenna's gain such as in a Yagi-Uda or an axial-mode helical antenna is dependent on the number of director elements and the number of helical turns present, respectively.

The antenna's impedance matching has an impact over the antenna's gain too. The reader antenna's gain must be the same for all the frequencies in the band of operation. This is essential because the signal that is transmitted by the RFID reader would hop between various frequency channels at different times due to the underlying frequency-hopping spread spectrum (FHSS) reader to a tag communication technique. An antenna with a narrow gain bandwidth (say 6 dBi at the center of the band and 4 dBi at towards edge) may lead to different tag read distances at different instances. The FCC frequencies have 50 frequency channels and it takes at least 60 seconds to successfully hop between all the frequencies. Narrow gain bandwidth leads to intermittent tag detection as it is practically impossible for some applications such as vehicle tolling, to continually read tags for 60 seconds.

5) VSWR: The voltage standing wave ratio (VSWR) of an antenna is the function of the reflection coefficient of an antenna. The antenna's input impedance must match the UHF RFID reader's nominal impedance (50 Ω) to get a VSWR closer to 1 across the operating frequencies. When the antenna's input impedance is not adequately matched, the reflected power would be directed back to the reader's port to damage the reader's receiver. The antenna's VSWR bandwidth must be at least 4 MHz and 27 MHz for ETSI and FCC frequencies, respectively. The threshold used to determine the VSWR bandwidth varies from reader to reader. Impinj r420 readers have specified the antenna's return loss to be at least 10 dB (1.92 VSWR) while the Thing-Magic M6e requires 17 dB (1.33 VSWR) across the operational frequencies [37]. When the RFID readers use the VSWR parameter in their antenna detection algorithm, a poor VSWR reading at certain frequencies (during the frequency hopping) leads to continuous antenna connection and disconnection from the reader's port, enabling disruption in tag detection reliability.

6) Radiation Pattern: An antenna's radiation pattern (Fig. 1) is a graphical representation of the antenna's radiated power in a three-dimensional space at far-field distances. Main lobe or the major lobe is where the antenna's radiation is maximum. The maximum directive gain of an antenna lies within the peak of the main lobe radiation [42].

A reader antenna's ability to detect tags in a given area is dependent on its far-field and near-field/Fresnel radiation. Identifying unwanted tags present in a given area is also dependent on the radiation parameters. Reader antennas designed

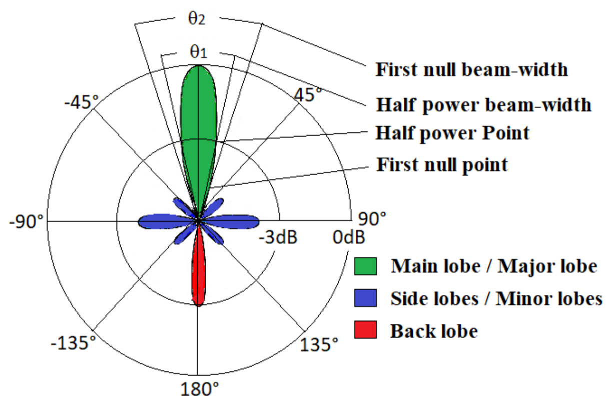

Fig. 1. Radiation pattern of a directional antenna.

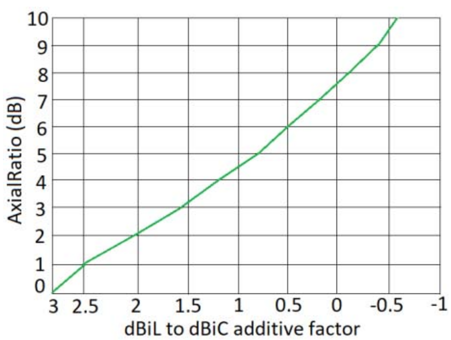

Fig. 2. dBiL to dBiC additive factors for various axial ratios.

for applications like warehouse inventory management must have a wider far-field and near-field radiation to cover a large area whereas the antenna used in a shelving/cabinetry application for asset localization requires a confined read zone. Sidelobe suppression is also essential for vehicle-tolling applications where intended zones are created using narrow main lobes.

7) Axial Ratio: Axial ratio (AR) is a parameter that is related to circularly polarized antennas. It is the ratio between the minor and the major axis of a polarization ellipse. The axial ratio in practical reader antennas is quoted in the magnitude difference between the orthogonal polarizations. A 0 dB AR means the orthogonal magnitudes of that antenna is equal. The axial ratio parameter is a requisite when the gain of a circularly polarized antenna is expressed in dBiC. A circularly polarized antenna with 6 dBiL and 0 dB AR can be expressed as 9 dBiC. Since the magnitude is equal in orthogonal directions, 3 dB can be added to the linear gain of the antenna [43]. dBiL to dBiC gain conversion can be made using the chart shown in Fig. 2. Axial ratio is a key parameter for practical reader antennas used in applications where the tag's orientation is unpredictable. Axial ratio up to 2 dB is optimal and an AR beyond that will yield unreliable and intermittent tag detection. Axial ratio is also crucial for the effective radiated power (ERP) and the effective isotropic radiated power (EIRP) calculations to meet the regulatory requirements defined by local regulatory bodies.

TABLE IV
RESTRICTION OF HAZARDOUS SUBSTANCES – RoHS-3

Restricted Substances	ppm
Lead (pb)	< 1000
Mercury (Hg)	< 100
Cadmium (cd)	< 100
Hexavalent Chromium (Cr VI)	< 1000
Polybrominated Biphenyls (PBB)	< 1000
Polybrominated Diphenyl Ethers (PBDE)	< 1000
Bis ()2-Ethylhexyl) phthalate (DEHP)	< 1000
Benzyl butyl phthalate (BBP)	< 1000
Dibutyl phthalate (DBP)	< 1000
Di-isobutyl phthalate (DIBP)	< 1000

8) Maximum Input Power: Maximum input power rating is the maximum allowable power that can be provided into an antenna for transmission without damaging the antenna's components. The substrate and the passive components used in an antenna design are susceptible to detrimental effects when input power is exceeded than the rated power. A practical reader antenna's power may be increased to achieve a greater read distance or to detect tags in a dense environment such as palletized assets. High gain antennas fed with a higher reader power cannot comply with the ERP and EIRP based power regulations prescribed by the regional regulatory authorities. For instance, an antenna with a 6 dBi gain can only be provided with 1 W reader power when used in the USA region to comply with the 4 Watts EIRP regulation prescribed by the FCC regulatory authority [39]. An antenna with a 0 dBi gain can be provided up to 4 Watts reader power and can still meet the FCC's EIRP specification. Thus, the input power rating for high gain antennas is not critical compared to the antennas with a lower gain.

E. Other Compliance and Certification Requirements

1) CE Compliance: Conformité Européenne (CE) is a certification mark indicating that a product that is sold within Europe meets the standards of safety, health, and environmental protection. Products can bear CE marking if the manufacturers declare the CE conformity through self-certification. There are a variety of CE directives among which the RED 2014/53/EU (radio equipment directive) [44] and the RoHS-3 2015/863 (restrictions of hazardous substances) [45] directives are relevant for a piece of RFID equipment. Antennas with one or more active components interacting with the RF signal are known as active antennas and those without any active components are called passive antennas. Active antennas are required to adhere to the RED norms. When the passive antennas are made available on its own, it is exempted from compliance. Passive antennas are subject to RED CE compliance if they are permanently attached to the RFID readers. The RoHS standards restrict the use of specific hazardous materials found in electrical and electronic products. Table IV shows the restricted substances and their levels in parts per million (ppm).

2) Explosive Standards and Certification: Explosions can be caused by electrical equipment in certain atmospheres and thus it is advisable to test the RFID equipment against explosive standards. IECEx (IEC-60079 explosive standards) [46] and ATEX 2014/34/EU (ATmosphères EXplosibles) [47] are some of the explosive standards widely used around the globe. Explosive certified reader antennas and readers must be used in explosive hazardous applications such as oil refineries, mining industries, hospital operating rooms, pharmaceutical industries, chemical processing industries and in aircraft workshops.

3) HERO Certification: HERO stands for the hazard of electromagnetic radiation to the ordnance. It is an EMC/EMI (electromagnetic compatibility/ interference) compliance certification defined by the military standard MIL-STD-464 for electrical and electronic equipment used in seaborne, airborne, ground and space-defense environment [48]. The antennas can be HERO certified along with an RFID reader. HERO certified RFID system is preferred in military applications.

4) Plenum Rating: Plenum spaces are areas in a building that facilitates air circulation. When cables such as ethernet cat5e, RF coaxial cables are routed through these spaces, the cables must comply with the NFPA-90A (national fire protection association) standards [49]. The plenum rated cable's outer jackets are made from fire-retardant and low-smoke polyolefins. Reader antennas that are cable-fed must be plenum rated to comply with the building's regulations.

V. Reader Antenna Design Methodology

The flow chart in Fig. 3 illustrates the reader antenna design methodology. The RFID reader antenna's intended use case is analyzed, firstly. The second step is to analyze the reader antenna's design requirements viz., physical, environmental, electrical and RF requirements. The design specifications for the reader antenna is then formulated and the antenna is designed to meet the specifications. If the specifications are met, then the antenna is tested for RFID performance. If the specifications are not met, then the antenna design is tweaked to meet all the specifications.

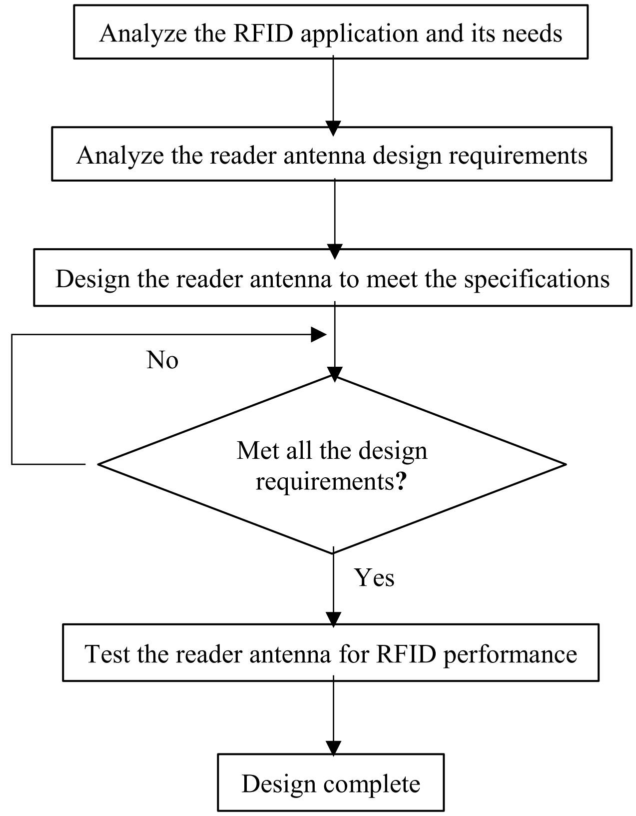

Fig. 3. Reader antenna design methodology.

VI. Application Specific Antenna Design–an Example

In this section, an application will be considered for an example reader antenna design that is designed using the reader antenna design methodology shown in Fig. 3. Let's contemplate a self-billing kiosk application in a retail environment.

A. Application's Needs and the Reader Antenna Design Requirements

Reader antennas used for billing and purchasing the goods at the kiosks must be able to detect a wide range of assets bearing different types of tags. Stray or unwanted tag detection outside the intended read zone is not acceptable and thus the antenna's radiation must be confined in a defined volume. Kiosk antennas must be planar and smaller in size to conform to retail aesthetics. The ability to embed the antenna within a desktop reader is required. As the antenna will be deployed in a controlled indoor environment, environmental requirements such as temperature, humidity, salt mist, solar radiation and wind survival are insignificant. The antenna must meet the flammability and plenum rating according to the building codes. Being an indoor antenna, splash proof IP-54 rating is plenteous to protect any dust or water ingress. The antenna 's polarization must be circular or dual-linear to detect tags in random orientations. Patch antenna design is preferred for this application as they are low-profile and planar in nature.

Although patch antennas have dead zones on the center of its surface due to very less magnetic field distribution, non-stationary near-field tags during scanning can be efficiently detected. The size of the half-wavelength radiating patch is dependent on the substrate's dielectric constant (ε_r). FR-4 is a fiberglass epoxy resin substrate that is self-extinguishing and UL94 V-0 flammability rated. This low-cost widely available substrate has a ε_r of 4.4 and a dissipation factor (DF) of 0.017.

An antenna designed in materials with a higher ε_r and DF will have a lower gain which is adequate for this application. The probability of stray/unwanted tag detection is lower with a low-gain antenna. This substrate is available in different thicknesses as laminates with copper cladding on either side. A 3 mm thick, double cladded FR-4 is chosen for the antenna design to achieve a satisfactory operational bandwidth. ETSI, 865-868 MHz operating frequencies are chosen for design purposes.

As the tag's orientation is unpredictable during item scanning, a circularly polarized or dual-linearly polarized antenna design is preferred. The axial ratio of a circularly polarized antenna gets spoiled when assets are in the antenna's

TABLE V
COMPARISON OF EXISTING AND EXAMPLE UHF RFID READER ANTENNA DESIGN

References	**Peak Far-field Gain**	**Polarization**	**Beam-width (Azimuth / Elevation)**	**Size Length x Width x Height**	**Tags used for testing**	**Reader embeddable?**	**Design Complexity**	**Matching load required?**	**DC bias required?**	**Comments**
[51] Spiral and patch antenna	3 dBiC	Circular	Not measured	Large: 275 x 135 x 1.6 mm	Small dipole-like tag	No, too large	High	Yes, a resistor or Two patch antennas	No	***Pros:*** Surface magnetic field distribution is uniform. ***Cons:*** Proximity assets spoils the axial ratio. Design requires a matching load and the size is too big to embed within an RFID reader.
[52] Spiral	1 dBiC	Circular	Not Measured	Large: 250 x 250 x 41.53 mm	Long dipole-like tag	No, too large	Very High	Yes	Yes, 3V	***Pros:*** Surface magnetic field distribution is uniform. ***Cons:*** Proximity assets spoils the axial ratio. Design requires a matching load and3V DC bias. The size is too big to embed within a reader.
[53] Snake line	-13 dBi	Linear	Not Measured	Large: 275 x 135 x 12.8 mm	Small and large dipole-like tags	No, too large	High	Yes	No	***Pros:*** Surface magnetic field distribution is uniform ***Cons:*** These near-field antenna's gain is very low to detect high dense assets. They are linearly polarized. The reader antenna's read zone definition is dependent on the tag antenna's gain. A matching load is required, and the size is too big to embed within an RFID reader.
[54] Traveling wave antenna	-14 dBi	Linear	Not Measured	Large: 275 x 136 x 1.53 mm	Small dipole-like tag	No, too large	High	Yes	No	
Example design	1.39 dBi	Dual-Linear	100°/140°	Small: 96 x 99 x 3 mm	A wide range of tags: Long dipole-like far-field tag, On-Metal tag, a laundry tag, near-field loop tag.	Yes, compact in size	Very low	No	No	***Pros:*** Although the surface magnetic field distribution reduced in the center non-stationary near-field tags during scanning can be efficiently detected. Dual-linear antenna is reliant to proximity assets, unlike a circularly polarized antenna. The antenna's gain is not too high to introduce stray tag reads and not too low (like a near-field antenna) to suffer from reading intended tags. Antenna's beam-width is wide enough to cover the Kiosk counter. The antenna neither requires a resistive matching load nor a DC bias. The antenna is versatile and can work with a wide range of tags.

proximity, leading to potential misreads. A dual-linearly polarized antenna is resilient to such actions and can detect the tags reliably. Single patch antenna with wider HPBW (in both azimuth and elevation planes) is adequate for easy item scanning. The antenna's fastening or mounting facility, aesthetics, and the ingress protection are not discussed in this section as the antenna's radome design provides these features. Antenna's radome can be machined or injection molded from plastics such as polycarbonate, ABS or PTFE. Features to accommodate 'O'-rings and rubber gaskets will be integrated into the radome's mechanical design.

B. Reader Antenna Design and Fabrication

A dual-linearly polarized antenna is designed in the FR-4 PCB substrate by etching the copper traces on the top cladding. The bottom cladding serves as the ground plane for the antenna. The ground plane takes the shape and size of the substrate, which is 99 x 96 mm. The radiating patch is square shaped with truncated corners, spanning 74 x 74 mm. The patch is microstrip-fed at its orthogonal vertices to obtain dual slant polarizations. 50 Ω SMA connectors are used to feed the microstrip lines. The microstrip lines are tuned using open-stubs to achieve an impedance match between the patch antenna edge impedance and the input impedance. The patch antenna consists of a 23 mm diameter guide hole for ease of embedding onto an RFID reader. Feedback LEDs can be placed in this hole to display successful and the unsuccessful tag reads by a change of color. The fabricated antenna is shown in Fig. 5.

The proposed antenna design is different from other generic UHF RFID reader antenna designs as they are not designed specifically to meet the practical requirements of every application. Desktop reader antenna designs reported in [51]–[54] meets some but not all the practical requirements for self-billing kiosk applications. Table V details the advantages of the proposed design compared to the existing desktop reader antenna designs.

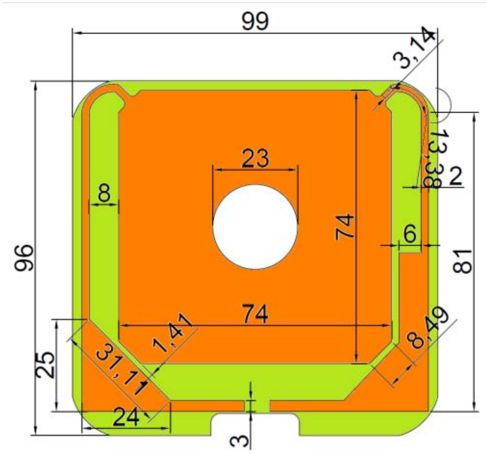

Fig. 4. Patch antenna design in FR-4 PCB substrate (dimensions are in mm).

(a) (b)

Fig. 5. Fabricated patch antenna–(a) Front view (b) Rear view.

C. Antenna's Working Mechanism

As the antenna is a square geometry with a symmetric slot in its center, the resonant length of the patch antenna is equal in all direction. Thus, the antenna generates two different slant-polarized radiation ($-45°$ slant and $+45°$ slant) when the ports are excited individually using a two-port RFID reader. The RFID reader by design switches its signal rapidly between the ports which enable single port excitation at different times. The slant-polarizations are orthogonal to each other. The orthogonality creates high isolation between the ports, meaning, the energy that is sent through the right port is either radiated or reflected through the same port, but it does not get drained through the left port and vice-versa. Less than 1% signal is reflected through the input ports, and the measurement results are reported in the following section. Although the antenna's dominant polarization is in $\pm 45°$, the antenna has some gain in vertical and horizontal polarization too. Therefore, randomly oriented tags can be easily detected.

D. Antenna Measurements and RFID Testing

The dual slant-polarized antenna is tested in an anechoic chamber using a Copper Mountain-TR1300 VNA for its return loss and port isolations. The antenna resonates in the ETSI frequencies with a maximum return loss of 21.07 dB and 19.95 dB in left and right ports, respectively. A 20 MHz, 10 dB return loss bandwidth is achieved (Fig. 6). The isolation between the ports is less than 11.98 dB across the frequencies,

TABLE VI
RETURN LOSS, ISOLATION AND GAIN MEASUREMENTS

Measurement	865 MHz	866 MHz	866 MHz	868 MHz
Port L – Return loss $\lvert S_{11}\rvert$ (dB)	-20.65	-21.07	-20.64	-19.60
Port R – Return loss $\lvert S_{11}\rvert$ (dB)	-19.95	-19.52	-18.61	-17.47
Port L – Isolation $\lvert S_{21}\rvert$ (dB)	-12.11	-12.04	-11.99	-11.98
Port R – Isolation $\lvert S_{21}\rvert$ (dB)	-12.15	-12.09	-12.06	-12.05
Port L – Slant gain (dBi)	1.36	1.39	1.50	1.43
Port L – Horizontal gain (dBi)	0.22	0.22	0.21	0.20
Port L – Vertical gain (dBi)	-4.98	-4.86	-4.70	-4.73
Port R – Slant gain (dBi)	0.6	0.6	0.59	0.59
Port R – Horizontal gain(dBi)	0.29	0.26	0.30	0.14
Port R – Vertical gain (dBi)	-5.38	-5.39	-5.37	-5.34

TABLE VII
TAG'S MAXIMUM READ DISTANCE AND AVERAGE RSSI

Tagged Asset	Read distance (mm)	Avg. RSSI (dBm)
Plastic container with Alien-G tag	450 mm	-53.7
Fishing sinker with Xerafy Pico-on-plus tag	20 mm	-35.0
Linen fabric with Fujisu WT-A533 tag	100 mm	-48.5
Jewelry ring with Tagsys AK tag	40 mm	-56.3

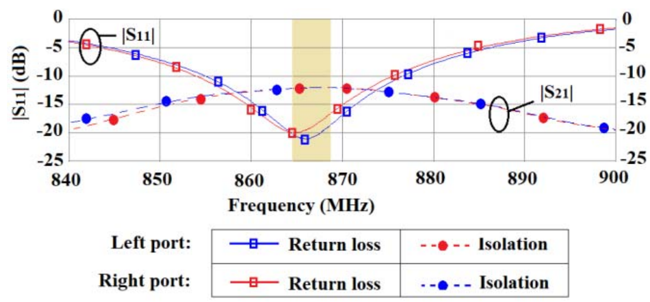

Fig. 6. Measured Return loss and Isolation.

in both ports. The antenna's gain is measured at different orientation viz., the slant, horizontal and vertical, in an anechoic chamber by the gain transfer method using a reference antenna (Fig. 7). The antenna has a peak gain of 1.5 dBi and 0.6 dBi in left and right ports respectively. Table VI shows the return loss, isolation and the gain values for all the ETSI frequencies.

The antenna's radiation pattern is measured at far-field in the anechoic chamber. The antenna is rotated in steps of 2.5° in both azimuth and elevation planes. The radiation pattern is measured for both left and right port excitation. Fig. 8 shows the radiation pattern of the patch antenna for both the ports at 866.5 MHz, the center frequency (f_c). The antenna's radiation is directional and symmetrical. The HPBW of the antenna is measured to be 100° and 140° in azimuth and elevation planes, respectively. The antenna's front-to-back ratio is 6 dB for both the ports. As kiosk applications require smaller sized antennas, the ground plane of the antenna is intentionally shrunk to trade-off the front-to-back ratio. The poor front to back ratio would not cause any detrimental effects in terms of stray tag

TABLE VIII
SUMMARY OF APPLICATION SPECIFIC ANTENNA DESIGN REQUIREMENTS

Applications	**Gain**	**Polarization**	**Directional Beam-width**	**Antenna surface energy distribution**	**Stray reads rejection**	**Dust and Water resistance**	**Temperature and Relative humidity (RH%)**	**Radome type**
Point of Sale (POS)	Low	Circular	Wide	No dead zones	Critical	IP54 (Splash proof)	10°C to 55°C and up to 65% RH	Not critical
Inventory management (warehouse)	High	Circular	Midrange	Not critical	Not Critical	IP65 (Intense splash proof)	-20°C to 60°C and up to 95% RH	Impact resistant
Shelving and cabinetry	Midrange	Circular	wide	No dead zones	Critical	IP54 (Splash proof)	10°C to 55°C and up to 65% RH	Load bearing
Portal (indoor)	High	Circular/Linear	Narrow	Not critical	Critical	IP54 (Splash proof)	10°C to 55°C and up to 65% RH	Not critical
Portal (outdoor)	High	Circular/Linear	Midrange	Not critical	Not Critical	IP67 (Water resistant)	-20°C to 60°C and up to 95% RH	Impact resistant
Race-timing (outdoor)	High	Linear	Midrange	Not critical	Highly Critical	IP67 (Water resistant)	-20°C to 60°C and up to 95% RH	Load bearing
Conveyor	Midrange	Circular	Wide	No dead zones	Critical	IP65 (Intense splash proof)	10°C to 55°C and up to 65% RH	Abrasion proof
Pharmaceutical fridges and freezers	Midrange	Circular	Wide	Not critical	Not Critical inside the fridge/	IP67 (Water resistant)	-40°C to 80°C and up to 95% RH	Non-brittle temperature resistant
Medical asset tracking	Midrange	Circular	Midrange	No dead zones	Critical	IP67 (Water resistant) and IP69K (High pressure high temperature splash)	-40°C to 90°C and up to 95% RH	Non-brittle temperature and pressure resistant
Vehicle tolling and vehicular	Very high	Linear	Narrow	Not critical	Highly Critical	IP67 (Water temperature)	-20°C to 70°C and up to 95% RH	Weather proof

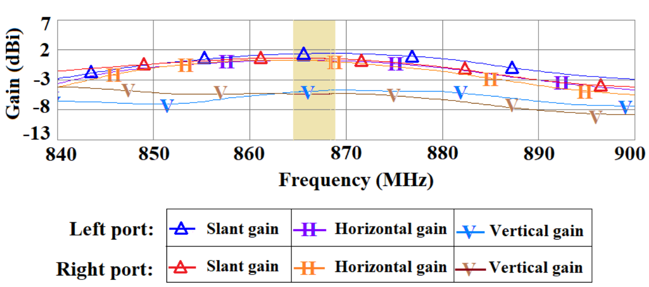

Fig. 7. Measured Linear gain at different antenna orientations for both ports.

detection, as the back radiation is contained within the kiosk's chassis.

The designed antenna is tested for its RFID performance using an Impinj r420 fixed RFID reader [55] and four different types of tags viz., the Higgs-3 Alien G-tag [56], the Xerafy pico-on-plus tag [57], Fujitsu WT-A533 linen tag [58] and the TagSys' AK-tag [59]. These tags are designed to function consistently when attached to the substrates namely, plastic, metals and fabrics. Tagged assets shown in Fig. 9 are tested for its readability to simulate a retail billing environment. Impinj's 'item test' software is used to configure and test the reader. The antenna's port-R and port-L are connected to reader port-1 and port-2, respectively. The reader power is switched between the ports at regular intervals and thus, the antenna generates the dual-polarized radiation. The reader is set to operate at the lowest power, 10 dBm in both the ports. The reader senses the antenna connection by measuring the antenna's VSWR. The tagged assets are read by the reader antenna at the boresight, effortlessly.

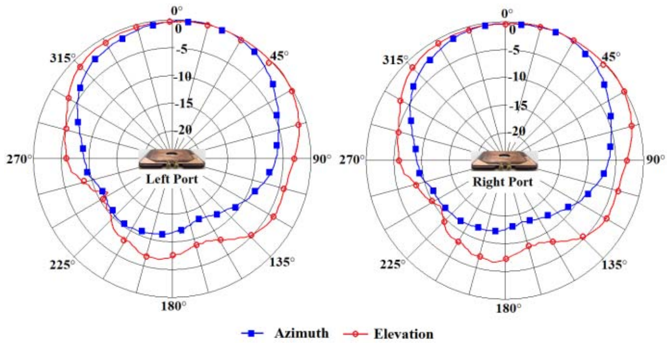

Fig. 8. Measured azimuth and elevation radiation pattern for both ports.

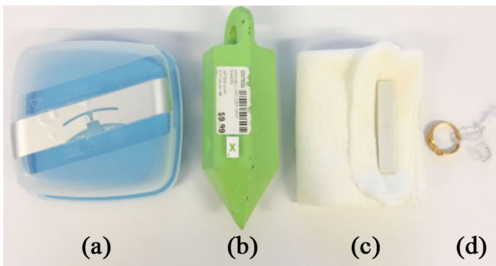

Fig. 9. Tagged assets–(a) plastic container, (b) fishing sinker, (c) linen towel and (d) jewelry ring.

The tag's maximum read distance and the return signal strength are tabulated in Table VII. The reader antenna's read zone mapped by moving the assets across the antenna abide the azimuth and elevation radiation patterns shown in Fig. 8. Read distance is dependent on the tag's sensitivity.

It was noticed that the Alien G-tag has much greater read coverage due to its higher chip sensitivity. Fujitsu WT-A533 tag was the next, followed by the Tagsys AK tag and the Xerafy pico-on-plus tag. The confined read coverage helps to eliminate unwanted tag detection. Table VIII summarizes the application specific antenna design requirements for most common RFID applications. Only the main RF, environmental and physical requirements are used to compare and show that different applications require different antenna design requirements.

VII. Conclusion

Practical UHF RFID fixed reader antenna design requirements viz., physical requirements, environmental requirements, electrical requirements and radio-frequency requirements are listed, and a design methodology is proposed. Using the comprehensive design methodology, an example embeddable reader antenna is designed for retail self-billing kiosks that meet all the requirements for a retail application. The antenna is tested for its RF parameters and RFID metrics. This paper can be used as a guide by antenna engineers for a commercial reader antenna design and manufacturing. As part of the future work, reader antenna requirements for a handheld RFID reader will be analyzed and a design methodology will be proposed with an example.

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