RFID smart data analysis for reading discrimination and direction detection

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Objective: the objective of the paper is twofold: on the one hand, to propose an algorithm capable of discriminating unwanted and cross RFID readings coming from different readers in a dense-reader environment. On the other one, a methodology is proposed in order to detect the direction of the movement of the tagged goods. The typical environment in which these algorithms can be profitably implemented is a RFID-enabled warehouse; in fact, in such scenario many readers are usually installed in closed proximity, each one monitoring a specific dock door. Many tagged items are simultaneously loaded and unloaded from trucks, thus a reliable algorithm capable of reducing interferences and detecting directions without the need for hard metal shields can make the RFID system more reliable and the deploy easier.

Design, methodology, approach: the proposed methodology has been developed and tested on raw RFID data coming from a couple of RFID readers installed in a lab in order to simulate a couple of dock doors; each reader is equipped with an array of 52 antennas facing different directions under different angles. A dummy pallet composed of cardboard boxes, apparel products and RFID tags has been passed under one reader in different directions, and resulting data from both readers has been processed. Different pallet configurations and speeds, reader settings and reading parameters have been tested, and different algorithms have been developed to analyse raw data.

Findings: by simulating a real-world environment, test results give a direct insight of performances to be expected from the proposed algorithms under real use cases. The reliability of the proposed methodologies, defined as the correct detection of the direction of each tag and the elimination of cross readings, is very high, being more than 90%.

Keywords: RFID, logistics, dock door, direction detection, cross readings.

1. Introduction

Radio Frequency Identification (RFID) is the use of an object (typically referred to as an RFID tag), applied to or incorporated into a product, for the purpose of identification and tracking, using radio waves. There are several ways of identifying items using RFID, but most systems consist of two parts. RFID systems have two types of components, RFID transponders (tags), placed on objects and RFID transceivers (readers). RFID tags store information using a small integrated circuit and communicate using an antenna. RFID readers are capable of reading the information stored on tags placed in their vicinity and communicate it to a host computer. Most tags are passive, i.e. they do not require battery power. Instead, passive tags use the energy of the reader's signal to fetch, process, and communicate stored data.

Product data are stored into the tag chip in form of an Electronic Product Code (EPC). EPC data of products are then passed to and shared through the EPC Network, which, according to EPCGlobal (2004), is "a way of leveraging the internet to access a large amount of logistics information that can be shared among authorized partners". Once EPC data are collected by reading RFID tags of cases and pallets, EPC numbers become secure data on companies' middleware.

Today, RFID is widely used in enterprise supply chain management to improve the efficiency of inventory tracking and management. In the logistics pipeline, RFID technology is expected to have a major impact on the efficiency of the whole supply chain. Commonly quoted benefits of RFID encompass increased processes automation, enhanced labour efficiency and better accuracy of logistics processes (Agrawal, 2001; Bertolini et al., 2015; Prater et al., 2005). There are several reasons for this diffusion, such as the capability of RFID tags to provide more information about products than traditional barcodes, as well as to avoid manual operations required to read them (Boxall, 2000; Bylinsky, 2000; Jones, 1999; Moore, 1999), thus improving process automation (Jones et al., 2004; Karkkainen, 2003) and overall logistics performances, especially for perishable food (Bertolini et al., 2013).

In order to achieve the above-mentioned benefits in the supply chain, a typical installation consists of multiple

RFID reader operating in closed proximity, like in Figure 1. In logistics, a cross-docking warehouse or a transit point can have dozens of dock doors aligned on one wall, separated by a small gap (even less than one meter). Often RFID technology (i.e. RFID reading gate) is adopted in order to carefully check the goods loaded on or unloaded from a truck in such dock door configuration.

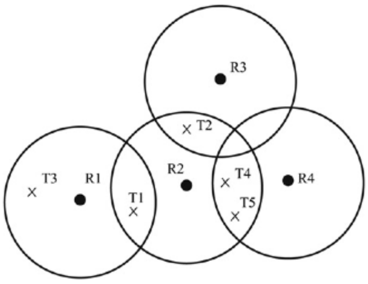


Figure 1: Example reader and tag deployment. Readers are denoted by small dark circles and their RF interrogation zones by larger disks. Tags are denoted by small crosses.

In this scenario one problem, reader collision, occurs when co-located readers are simultaneously active. Specifically, reader collisions occur at tags situated in the vicinity of two or more readers that simultaneously interrogate tags. Such tags may be unable to correctly decode reader queries, leading to undesirable and unpredictable behaviour. Current protocols for avoiding reader collisions are based either on time scheduling of reader transmissions, spatial isolation of readers or frequency assignment to readers, or a combination of these techniques. Solutions may either require a centralized entity or are completely decentralized, as reported by Carbunar et al. (2009). Even when the reader collision is avoided and tags correctly inventoried, another issue arises. Tags placed in the overlapping areas of two or more readers can be undesirably reported by multiple devices, since the kind of RFID tags adopted in the roll out of the project is usually the most performing one according to the specific application (Bertolini et al., 2012, Piramuthu et al., 2015).

This phenomenon happens when the readers reading areas overlap and some tags are placed in between. In dock door A, a tagged pallet may be loaded on a truck and detected by reader A and reader B, installed in the next door. In this situation, the pallet cannot be correctly assigned to a truck and thus the operator’s intervention is required to perform manual check and adjust RFID report; many interventions affect the efficiency of the RFID system and limit its benefits. There are different ways to avoid unwanted readings in a dense reader environment; the most common are the reduction of the transmitted power of the reader and the installation of physical metal shields between the doors. Both solutions have side effects that cannot be neglected; the first limits the unwanted readings but also the capability of the reader to detect the (desired) tags passing through the gate; on the contrary using metallic shields it is possible to use a higher reading power but a crafts man design and heavy installation is required.

In order to take advantage of high transmission power and to avoid the need for shielding infrastructures, a specific algorithm is presented. It is capable of discriminating unwanted and cross RFID readings coming from different readers in a dense-reader environment. Moreover, a methodology is proposed in order to detect the direction of the movement of the tagged goods. The typical environment in which these algorithms can be profitably implemented is a RFID-enabled warehouse; in fact, in such scenario many readers are usually installed in closed proximity, each one monitoring a specific dock door. Many tagged items are simultaneously loaded and unloaded from trucks, thus a reliable algorithm capable of reducing interferences and detecting directions without the need for hard metal shields can make the RFID system more reliable and the deploy easier.

The remainder of the paper is organized as follows. In the next section, the literary review is performed, describing the state of the art of localisation techniques based on radio frequency signals. Then the proposed algorithms and methodologies are presented, such as the in-field tests carried out for the purpose of this study. In the last section, the obtained results are discussed.

2. Literature review

RFID tags contain limited memory resources for storing unique identification, and information relating to the objects with which they are associated and attached. They also contain an antenna, used for communication with readers. There are two kinds of tags: passive and active (Uckelmann and Romagnoli, 2016). Passive tags do not need batteries, but are powered by RF energy from the reader. In addition to the memory chip and antenna, active tags are equipped also with a battery and a transmitter, allowing them to initiate transmissions. While active tags have a greater communication range and can operate autonomously, they are more expensive. The price efficiency of tags is the dominant factor determining their wide deployment. Most current RFID applications use only passive tags; thus, this paper focuses on passive tags. Signals from RFID readers activate compatible tags within their interrogation zone. The interrogation zone is defined to be the area around a reader where tags can receive the reader’s signal, process it and send back a response that can be correctly decoded by the reader. The information decoded by the reader is passed to host computing systems where it is further processed, according to the application. There are many techniques that can be adopted to analyze raw data coming from a RFID reader in order to filter and ignore unwanted tag readings and to detect the position (and thus the movement) of a tag in the interrogation zone.

Lopez et al. (2017) present a RFID indoor location system that makes use of Received Signal Strength (RSS) information. The system is derived from a simple direction finder system consisting on two antennas one tilted to respect to the other, so that their radiation patterns partially overlap. RFID tags are attached to the person or asset to be tracked. The ratio between RSS values received on each antenna is used to estimate the angle of arrival of the electromagnetic signals backscattered by RFID tags. Once the angle is estimated, the absolute RSS values are compared against a free-space propagation model to obtain an estimate of the range or distance. Then, given the angle and the range, the position of the RFID tags is obtained.

Another method for tracking RFID tags with millimetre level accuracy is presented by Wang et al. (2016). The surveillance region is partitioned into square grids at mm-level; then a virtual tag is supposed to be present in each grid as the same as the tracked one. On this basis, for the case where the tags move along a known track with constant speed, there is the need to locate the tag's initial position. The authors leverage phase periodicity of RF signal to obtain some candidates and then eliminate position ambiguity by double difference true phase. And for the case where the tag's moving track is unknown to the system, they adopt a first-order Taylor series expansion to calculate the relative displacements of the tracked tag and then locate the initial position as the same process as tracking the known trajectory.

Carbunar et al. (2009) address three important problems associated with tag detection in RFID systems: (i) accurate detection of RFID tags in the presence of reader interference; (ii) elimination of redundant tag reports by multiple readers; and (iii) minimization of redundant reports from multiple readers by identifying a minimal set of readers that cover all tags present in the system. The underlying difficulties associated with these problems arise from the lack of collision detection mechanisms, the potential inability of RFID readers to relay packets generated by other readers, and severe resource constraints on RFID tags. The authors present a randomized, distributed and localized reader collision avoidance algorithm and provide detailed probabilistic analysis to establish the accuracy and the efficiency of this algorithm.

The above-mentioned methodologies need accurate tuning and calibration of the system, and a precise installation of the RFID equipment in a controlled room. Such conditions cannot be always guaranteed in a real environment, such as warehouses and logistics processes, where signal reflections and absorptions can interfere with the RSS and thus the computation of tag position.

Wang et al. (2009) conduct performance analysis and test for passive RFID system in UHF band in free space and line-of-sight indoor environments. They present performance degradation of different materials, in terms of power received by tag and reader, communication range and link information rates. Particularly, the multipath fading and root mean square (RMS) delay spread in line-of-sight indoor environments are analysed by a 5-ray model with different polarization, such as horizontal polarization, vertical polarization and circular polarization. A practical test is carried out on an indoor balcony of an office building. In addition, the electric field environment is simulated to analyse multipath degradation; according to the test, the recognition rate is almost consistent with the results of theoretical analysis and simulation. The multipath degradation significantly affects the passive RFID system on communication range and recognition rate, and it is also one of the key limitations on system performance. Such limitation can affect the localisation techniques based on RSS and signal phase.

These are just a sampling of tangentially related literature that considers RFID use in the localisation of items. In order to use RFID systems in real use cases, and get reliable data from the field, a simple procedure is described to discriminate unwanted readings and detect the direction (not the position) of a moving item in the interrogation zone of a reader. In the remaining part of the present work the methodologies are presented and applied to simulated logistics processes.

3. Materials and methods

In order to develop a data analysis methodology to discriminate unwanted RFID readings and to detect the movement of the tags, a discrete amount of raw RFID data is required. This data shall be generated according to some rules: (i) simulating real logistic processes; (ii) adopting RFID equipment potentially installed in real scenarios. To this extent, we set up a RFID reading system composed of two Impinj xArray gateways accurately positioned to simulate a couple of dock doors. The readers are attached to the ceiling of a lab, the height is $z = 3$ m, while the distance between the two readers along x axis is 4 m, which is approximately the distance between two dock doors aligned on a warehouse wall. The lab area is 15 x 10 m wide, and no metallic items are present, except for the material handling equipment. The set-up of the system is shown in Figure 2 and Figure 3. Two different IP addresses were assigned to the readers, the reader placed at $x = 0$ m has IP ending in 29 (reader 1), while reader at $x = 4$ m has IP ending in 30 (reader 2).

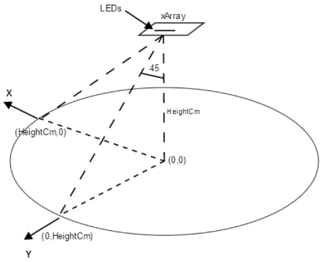


Figure 2: Impinj xArray interrogation zone and Cartesian coordinate system.

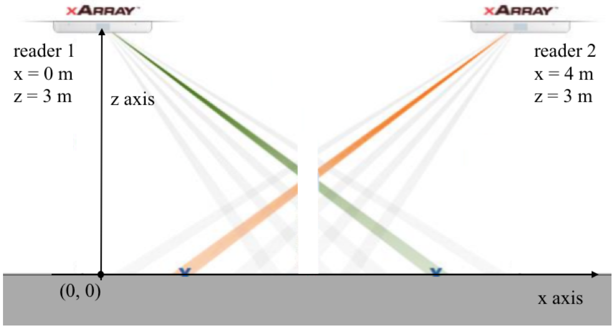


Figure 3: Impinj xArray installation set-up for data collection.

Each xArray reader is equipped with 52 antennas automatically switched by the reading board, the array of antennas is organised in rings and sectors, according to Figure 4. Each antenna of each ring and/or sector can be individually selected, the reader performs the inventory using the selected antennas; for each detected tag it reports EPC code, Timestamp, Antenna, RSS value. The reader can be configured and controlled by means of a specific software developed by Impinj and called Item Test. The available options are the typical RFID Gen2 parameters (reader mode, session, target) plus some specific options for the xArray, which take advantage of the antenna array.

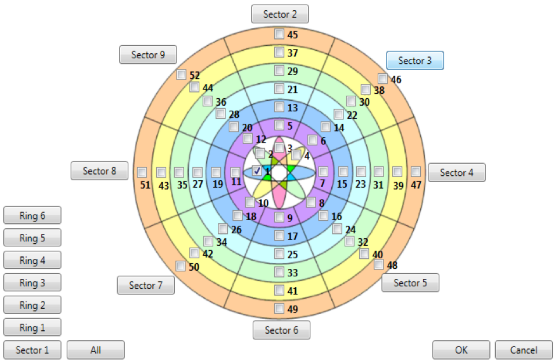


Figure 4: Impinj xArray sectors and rings to organize and group the 52 reading antennas. Selection form used to set-up the system in Item Test software.

Different reader configurations and test set up have been used in order to define the best algorithm for reading discrimination and direction detection.

3.1 Direction detection

In order to define a suitable algorithm to detect the direction of moving tags, reader 1 has been configured to use only the antennas belonging to sector 1, 2 and 6, while reader 2 was not used. These sectors are aligned to the direction of movement of the tagged goods moving under the xArray gateway. In particular, in each test the goods were moved at different speeds under the antennas passing through sector 2, 1 and 6 in this order.

Table 1: Tested configurations to collect data for direction detection.

Test ID	Tagged items	Tag type	Speed [m/s]	Reader mode	Runs
1	20	Smartrac Dogbone G2iL	1,15	Hybrid mode	10
2	20	Smartrac Dogbone G2iL	1,15	Dense M=4	10
3	402	Smartrac Web Ucode7	0,47	Autopilot Static	10
4	402	Smartrac Web Ucode7	0,95	Hybrid mode	10
5	402	Smartrac Web Ucode7	0,95	Autopilot Static	10

Transmitting power was set to 31.5 dBm. Different configurations have been tested, according to Table 1.

The raw amount of data coming from reader 1 has been analysed; for each tag the reader reports EPC code, Timestamp, Antenna, RSS value for each single reading. The typical plot of a tag RSS as function of time is reported in Figure 5. The sample tag is moving under the reader, being read from the antennas in sector 2, 1 and 6 in order. The readings can be overlapped when the tag is close to the reader and thus read by antennas in more than one sector.

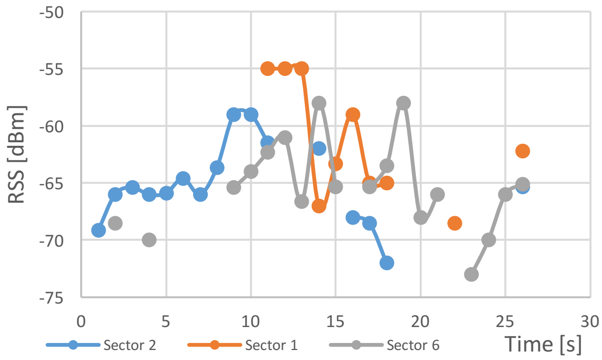


Figure 5: Example of a typical RSS pattern for a tag while passing through sectors 2, 1 and 6 in this order. The RSS is the average value measured by the antennas belonging to the specific sector.

In order to detect the direction of the moving tag, it is necessary to check the presence of the tag under each sector and correlate the measured RSS with time.

A representative time (T_R) is computed for each tag under each sector; it is the time assumed as representative of the presence of the tag in the specific sector. It is defined as the weighted average of the time the tag has been read from the antennas belonging to the specific sector, being the weights the RSS of each read. T_{R2}, T_{R1}, T_{R6} are computed, and the direction of the tag is assumed comparing them. In particular, three different checks can be done:

1. Check 1: $T_{R1} > T_{R2}$
2. Check 2: $T_{R6} > T_{R1}$
3. Check 3: $T_{R6} > T_{R2}$

Ideally a correct direction detection occurs when all three conditions are verified, since the real tag is moving from sector 2 to sector 1 to sector 6. This complete check can only be performed when the tag is correctly detected at least once in each sector; in case some sector's readings are missing but it is still possible to perform at least one check, direction can be computed according to this. Analysing raw data coming from reader 1 the check $T_{R6} > T_{R2}$ has been used to determine the direction of movement; this check gives good results because it consider the opposite sectors. When readings from sector 2 or 6 are not available, i.e. because the tag has not been inventoried, check 1 or 2 has been used instead. The following Figure 6, Figure 7 and Figure 8 report Accuracy (read tags out of all expected tags) and percentage of tags whose direction has been successfully detected when using Check 3 only or Check 3 or 2 or 1.

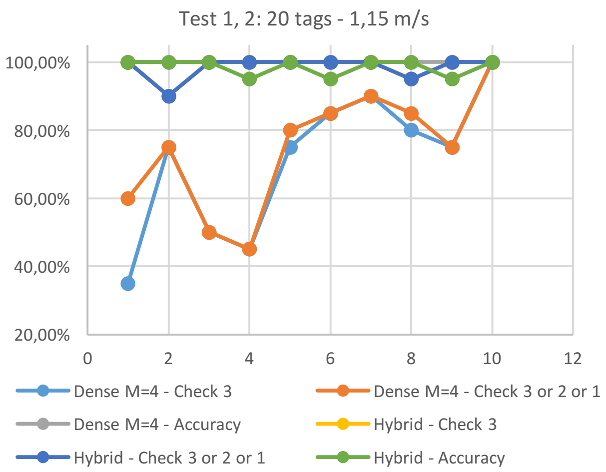


Figure 6: Accuracy and successful detection of Check 3 only or Check 3 or 2 or 1 for Test ID 1 and 2.

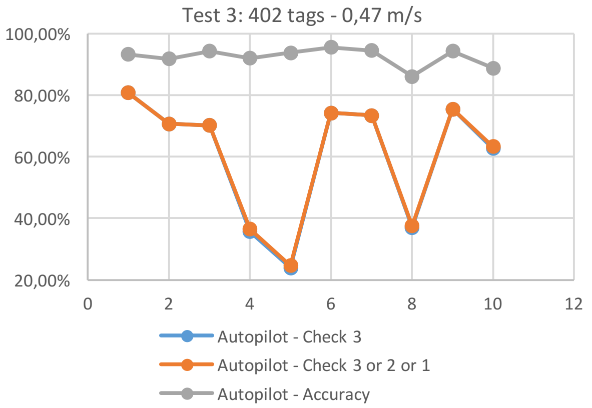


Figure 7: Accuracy and successful detection of Check 3 only or Check 3 or 2 or 1 for Test ID 3.

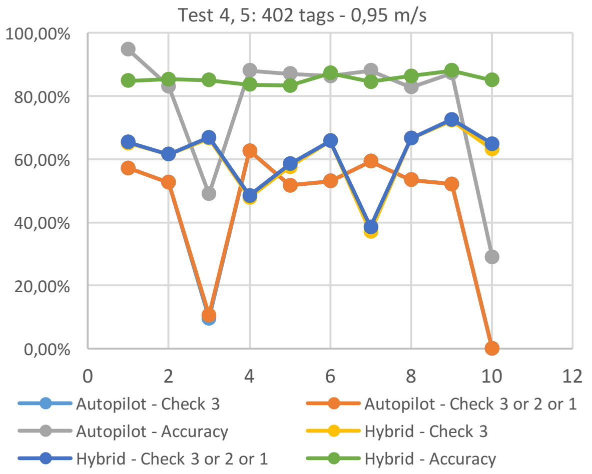


Figure 8: Accuracy and successful detection of Check 3 only or Check 3 or 2 or 1 for Test ID 4 and 5.

Table 2: Summary of results for Test ID 1, 2, 3, 4 and 5.

Reader mode/ tag n./speed [m/s]	Average of Check 3	Average of Check 3 or 2 or 1	Average of Accuracy
⊟ **AutoPilot Static**			
⊟ **402**			
0,47	64%	64%	93%
0,95	49%	49%	79%
⊟ **Dense M=4**			
⊟ **20**			
1,15	74%	77%	100%
⊟ **Hybrid Mode**			
⊟ **20**			
1,15	99%	99%	99%
⊟ **402**			
0,95	63%	63%	86%

According to Table 2, it can be noticed than the possibility to use Check 2 or 1 when Check 3 is missing increases the capability of the methodology to correctly detect the direction.

3.2 Reading discrimination

A methodology capable of discriminating unwanted readings has been developed. In order to get suitable raw data, the same hardware set-up previously described has been used, but this time both reader 1 and 2 have been activated at 31.5 dBm and all 52 reading antennas have been selected for each reader. Reader 2 has been used to detect wanted readings, since the tagged cardboard cases were handled on a pallet below this reader. On the contrary, reader 1 was used to gather unwanted readings, since no tagged items were directly passing under this gate, thus the reader was cross-reading the same cases passing below reader 2. No metal shields were placed between the two reading gates, in order to simulate the worst scenario for the RFID technology, which is actually very common in logistics. In fact, very often in a warehouse the dock doors are aligned on a wall, being detached by a gap that can be even less than one meter. Four different configurations of the system have been tested, as reported in Table 3; data has been collected and analysed for each configuration.

Table 3: Tested configurations to collect data for reading discrimination.

Test ID	Tagged items	Target	Speed [m/s]	Reader mode	Runs
1	20	Single target	1,15	Hybrid mode	10
2	20	Dual target	1,15	Hybrid mode	10
3	20	Single target	1,15	Dense M=4	10
4	20	Dual target	1,15	Dense M=4	10

The same cases previously tested in Test ID 1 and 2 have been used, thus only Smartrac Dogbone G2iL inlay has been tested. Such tag is commonly used for case-level tagging because of the good performance and affordable price. For each configuration, for each run and for each tag a couple of Overall Score Index (OSI_1, OSI_2) has been computed, one for reader 1 and one for reader 2. The OSI index is computed as the sum of four factors:

1. Minimum value of RSS [dBm]: the lowest value of the RSS received by the specific reader while reading the considered tag, in case the tag reading is missing the value has been set to -100 dBm;
2. Average value of RSS [dBm]: the average value of the RSS received by the specific reader while reading the considered tag, in case the tag reading is missing the value has been set to -100 dBm;
3. Maximum value of RSS [dBm]: the highest value of the RSS received by the specific reader while reading the considered tag, in case the tag reading is missing the value has been set to -100 dBm;
4. Reading count [number]: the number of times the specific reader has detected the considered tag.

The OSI index for each reader is then defined as it follows

1. $OSI_1 = w_1 (RSS_{MIN,1} + 100) + w_2 (RSS_{AVG,1} + 100) + w_3 (RSS_{MAX,1} + 100) + w_4 RC_1$
2. $OSI_2 = w_1 (RSS_{MIN,2} + 100) + w_2 (RSS_{AVG,2} + 100) + w_3 (RSS_{MAX,2} + 100) + w_4 RC_2$

Factors 1, 2 and 3 have been added 100 in order to have positive values instead of negative ones. Each factor has been weighted by means of $w_1 – w_4$, whose values have to be investigated during the setup and fine tuning of the system.

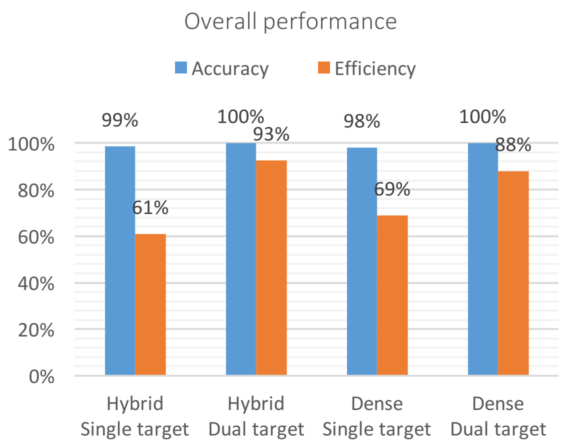
Each test run involved 20 tags and was repeated 10 times; thus, an overall number of 200 potential readings (performed by reader 2) is the benchmark for determining the accuracy of the system to detect all the tags.

Table 4: Summary of results for Test ID 1, 2, 3 and 4.

Test ID	1	2	3	4
w_1	5,0	1,0	0,6	1,0
w_2	1,0	2,0	0,7	0,5
w_3	0,5	0,2	0,6	0,6
w_4	1,0	0,1	1,0	1,0
Tags read	197	200	196	200
Accuracy	99%	100%	98%	100%
Success	120	185	135	176
Efficiency	61%	93%	69%	88%

Since the tagged pallet was moved below reader 2 under its interrogation zone, the algorithm returns a success in case $OSI_2 > OSI_1$. This means that the score reached by the tag under reader 2 is higher than under reader 1. To compute the percentage of success, the number of successful detections ($OSI_2 > OSI_1$) has been related to the accuracy of the system in the specific run. In fact the methodology can only be applied if the tag is detected. Table 4 and Figure 9 report the analytic and plotted results.

Figure 9: Overall performance achieved in discriminating unwanted readings.



4. Conclusions

The proposed methodologies achieved good results.

In particular, the direction detection methodology achieves better results when the number of tag to be detected and the speed are lower, and when the reader is set in a mode that increases the number of readings of every single tag (i.e. Hybrid mode and Dual target instead of Autopilot Static or Dense). In fact, when more readings are available for each tag the calculation of the representative time T_R works better because the trend of RSS against time is less affected by spikes and signal reflections. According to Table 2 it can be noticed that the methodology gives absolute results that can be profitably used for a case-level tagging scenario (20 tags) but not for an item-level scenario (402 tags). In fact, when 20 tags are considered and the reader is set to Hybrid mode the accuracy and the direction detection indicators are very high (99%); under these circumstances it is possible to implement the methodology in a real scenario and use it in real shipping/receiving processes. In order to implement this smart methodology, it is mandatory to equip the gate with a RFID reader capable of driving more antennas and place them in sectors aligned with the direction of movement of the freights. Only adopting a set-up like this it is possible to compute T_R for following sectors and compare them to assume the direction.

Regarding the reading discrimination methodology, it can be noticed that again the better results are achieved when the reader is set in a mode that increases the number of readings of every single tag (i.e. Hybrid mode and Dual target instead of Dense and/or Single target). The most performing configuration has Test ID 2, achieving 100% accuracy and 93% efficiency. It has to be noticed that 93% of the tags has been assigned to reader 2 although they have been read also by reader 1, thanks to the difference in OSI indexes. The installation of a metal shield between the two readers (i.e. dock doors) may increase the gap between the OSI indexes and thus increasing the precision of the methodology.

All the tests have been done using 20 tags in order to simulate logistics processes involving tagged cases; some pre-test trials showed that this methodology doesn't work fine in an item-level tagging scenario (i.e. 402 tags). Since the indication of the antenna and sector is not used for this analysis, the proposed methodology can be also easily implemented using common RFID readers equipped with 4 antenna ports, and also existing installations can be easily upgraded since there is no need for hardware changes.

Many RFID installations rely on massive and wide metallic shields to concentrate the reading zone in the desired areas, reaching an accuracy close to 100%. The proposed algorithm can achieve an accuracy of 93% in the best scenario without any shield. This is a good result considering that it is not meant to replace the shields, since it can be used in conjunction with them in order to better filter data and discriminate unwanted reads due to signal reflections or wrong material handling (i.e. staging pallets near a RFID dock door). Adopting the methodology may lead to cost saving and easier deployment due to the reduction in size of the required shields.

In a future development of the present work both methodologies could be validated in a real scenario, testing them with real shipping and/or receiving processes through real dock doors in a 3PL warehouse. Moreover, a genetic and/or heuristic algorithm could be developed to get the optimum values of the parameters $w_1 - w_4$ used for the discrimination. In conclusion, the proposed methodologies, which are not highly innovative but are worthy because of the simplicity of deployment, show a good potential and thus could be deeply investigated in order to be better validated and tested.

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