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Smart RFID gate exploiting a Near-Field Focused Array

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Abstract

This paper presents a low-cost implementation of an UHF-RFID gate featuring an effective tag moving direction classification. The smart RFID gate combines a Near-Field Focused array antenna with a phase-based direction estimation method. Preliminary measurements confirm good performance in terms of stray read reduction and movement direction capabilities.

1 Introduction

The recent advances in Radio Frequency Identification (RFID) technology have enabled a large variety of new applications, especially in the framework of the Industrial Internet of Things (IIoT) [1]. A huge impact of RFID technology can be found in manufacturing, anti-counterfeiting, access control, airport baggage management, logistics, supply-chain management, and so on [2].

UHF-RFID technology has been suggested to trace people in different scenarios, such as manufacturing plants, warehouses, and hospitals, by simply using a badge with a battery-less tag. Many solutions exist, mainly consisting in RFID-based checkpoints placed at some strategical locations, i.e., RFID gates. Each RFID gate is usually composed by an Ultra High Frequency (UHF) RFID reader and at least one antenna. However, a complete awareness of the people occupancy inside assigned areas needs for an RFID gate that can also provide the transit direction of the identified tagged person.

Due to the large beamwidth of standard reader antennas in the UHF band and the multipath effects typical of an indoor scenario, the target tag crossing the gate could be identified together with other static or moving tags that are nearby the gate, so causing stray reads [3].

To solve this problem, solutions relying on shielded reading zones, e.g., tunnel gates [4], were proposed. However, they require for a significant modification of the environment, which is not always possible due to encumbrance and cost requirements. As an alternative, gates adopting multiple antennas have been suggested [5]. Moreover, smart gates implementing phase-based classification methods have been recently proposed, with the adoption of a carpet of reference tags [6] or a proper orientation of the reader antenna [7].

Next to this, Near-Field Focused (NFF) antennas [8], [9] have been designed and discussed for several applications among which the RFID systems [10], [11]. Compared to conventional far-field (FF) focused array antennas, NFF arrays allow to maximize the radiating field at an assigned focal region, by minimizing the interference with the surrounding environment. This feature makes them particularly suitable to realize UHF-RFID smart gates able to read tags passing underneath the gate, while significantly reducing the stray read phenomena.

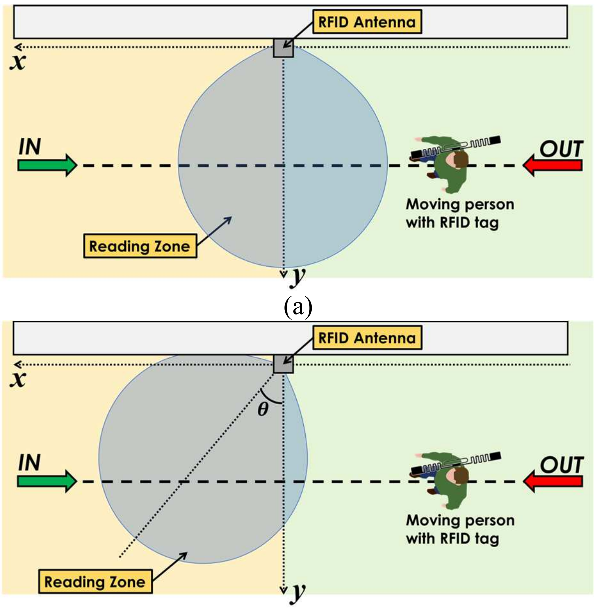
This paper presents a smart gate equipped with a NFF array antenna, instead of a conventional far-field focused array. The spatial selective features of the NFF arrays are profitably combined with an effective phase-based method to determine the moving direction of tagged people crossing the RFID gate. The method is validated in an experimental indoor setup and compared when a commercial UHF-RFID antenna is used instead.

The paper is organized as follows. Section II introduces the RFID gate infrastructure with the NFF array and the phase-based direction classification method. Section III describes the experimental setup together with the design of the NFF array and shows the method performance. Finally, Section IV states conclusions and future work.

2 Smart RFID Gate

As an example, let us consider a corridor where it is required to monitor the passage of people and their direction of movement, as depicted in Figure 1. The x-axis of the chosen reference system overlaps with the longitudinal direction of the corridor. People can enter the area when they move along the negative direction of the x-axis (IN), while they exit the area when they move in the opposite direction (OUT). Let us suppose that the RFID antenna is attached to the lateral wall, perpendicular to the floor, and pointing towards the center of the corridor with a vanishing tilt angle. Thus, the radiating field is symmetric with respect to the y-axis as shown in Figure 1a.

When the tagged person crosses the gate, the relative distance r_n between the moving tag $\mathbf{p_n} = [x_n, y_n, z_n]$ and the antenna $\mathbf{p_a} = [x_a, y_a, z_a]$ varies:



(a)

(b)

Figure 1. Top view of the RFID gate scenario when (a) the antenna points toward the y-direction and the reading zone is symmetrical, and (b) when the antenna points laterally, and the reading zone is asymmetrical.

$$r_n = \|\mathbf{p_a} - \mathbf{p_n}\| \quad n = 1, \ldots, N_r \tag{1}$$

where N_r is the number of successful tag queries and $\| \, . \, \|$ is the norm operator of the distance vector. The phase of the complex signal backscattered by the tag measured at the reader side depends on the distance r_n according to:

$$\phi_n = \mathrm{mod}\left(\phi_0 + \frac{4\pi r_n}{\lambda}, 2\pi\right), \quad n = 1, \ldots, N_r \tag{2}$$

where λ is the free-space wavelength of the radiated field and ϕ_0 is the phase offset including the effect of cables and other reader components [12]. By assuming ϕ_0 as constant within the reader antenna main beam, it can be removed if the measured phase ϕ_n is normalized with respect to the first sample ($n = 1$) according to:

$$\Delta\phi_n = \phi_n - \phi_1, \quad n = 1, \ldots, N_r \tag{3}$$

The normalized phase sequence $\Delta\phi_n$ can be unwrapped to obtain the normalized unwrapped phase sequence $\Delta\phi_n^u$. For an accurate phase unwrapping, consecutive phase samples must not differ more than π rad.

Due to the symmetric radiation pattern of the reader antenna with respect to the moving plane, the normalized unwrapped phase sequence $\Delta\phi_n^u$ presents a symmetric behavior, thus resulting in the impossibility to discriminate between the two types of action, i.e., to distinguish between IN and OUT actions.

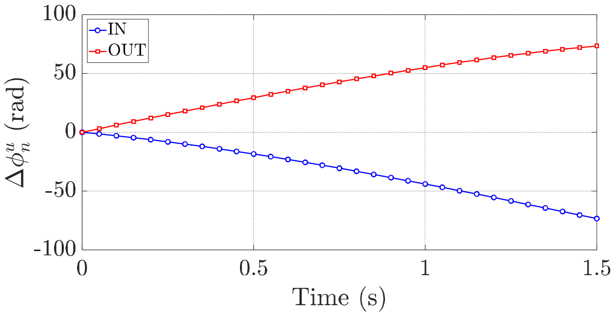


Figure 2. Temporal behavior of the normalized unwrapped phase sequence in the scenario represented in Figure 1b for IN and OUT actions.

Let us consider the case of a reader antenna radiating toward a direction tilted with respect to the case in Figure 1a. The latter behavior can be realized by rotating the reader antenna with respect to the y-axis by a θ angle in the horizontal plane as suggested in [7] (Figure 1b). Alternatively, a NFF array with a lateral focal spot can de designed, as proposed in this paper. Thus, the normalized unwrapped phase sequence $\Delta\phi_n^u$ will present an asymmetric behavior with respect to the moving direction, which allows for a correct discrimination between incoming and outgoing people. In particular, during an entrance action (IN) the tag carried by the person will be detected only when approaching the antenna, i.e., when r_n decreases, measuring a decreasing $\Delta\phi_n^u$. On the other hand, during an exit action (OUT) the tag on board the person will be read only when moving away from the antenna, that is when r_n increases, measuring an increasing $\Delta\phi_n^u$.

The classification algorithm comes straightforward for the asymmetrical gate configuration (Figure 1b): if the measured $\Delta\phi_n^u$ is a decreasing function, the estimated action is IN, otherwise the estimated action is OUT. To do that, we first interpolate the measured $\Delta\phi_n^u$ with a first-order polynomial function, i.e., an interpolating line. Then, we take the slope m of the line and do the following classification:

$$\begin{cases} \text{Classified action } = \; IN, & \text{if } m \leq 0 \\ \text{Classified action } = \; OUT, & \text{if } m > 0 \end{cases} \tag{4}$$

Figure 2 shows two examples of temporal behavior of the normalized unwrapped phase in the scenario depicted in Figure 1b (asymmetrical RFID gate) for IN and OUT actions.

3 Preliminary Experimental Results

To validate the proposed method, an experimental setup was built at the facilities of the University of Oviedo (Figure 3).

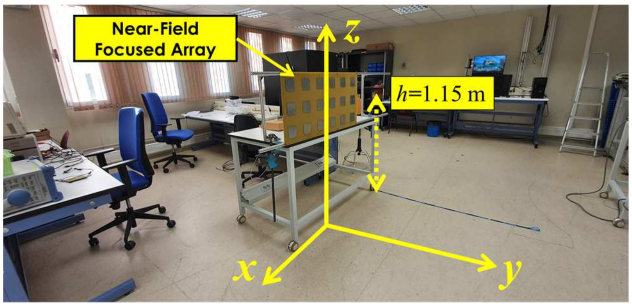


Figure 3. Experimental setup with the UHF-RFID NFF array built at the University of Oviedo.

The NFF array is a custom 6 × 3 array of circularly polarized (LHCP) patch antennas printed on a 3.2 mm-thick FR4 substrate ($\varepsilon_r = 4.3$ and $tan\delta = 0.025$), designed to work in the UHF-RFID ETSI band (865-868 MHz). The array element is an edge-trimmed square patch, with a side of 78 mm. The patch exhibits a half-power beamwidth (HPBW) of about 120°, in both principal planes. A single-port feed has been implemented through a 50 Ω coaxial cable. The spacing between the elements is $\lambda/2$. The NFF array is divided in two 3 × 3 sub-arrays, whose feeding networks have been designed with a 50 Ω microstrip line to set the focal point at the points P_{f1}=[0,1.5, 0] m and P_{f2}=[0.1,0.6, 0] m, respectively. The resulting focused reading zone is apparent from the normalized spatial distribution of the electric field depicted in Figure 4. In this way, the reading zone is asymmetrical with respect to the y-axis of Figure 3, and the antenna can be fruitfully exploited to apply the proposed direction classification method. Moreover, the highly spatial selective field of the focused antenna significantly reduce stray reads and missing readings, which are due to the multipath phenomenon that is typical of indoor scenarios.

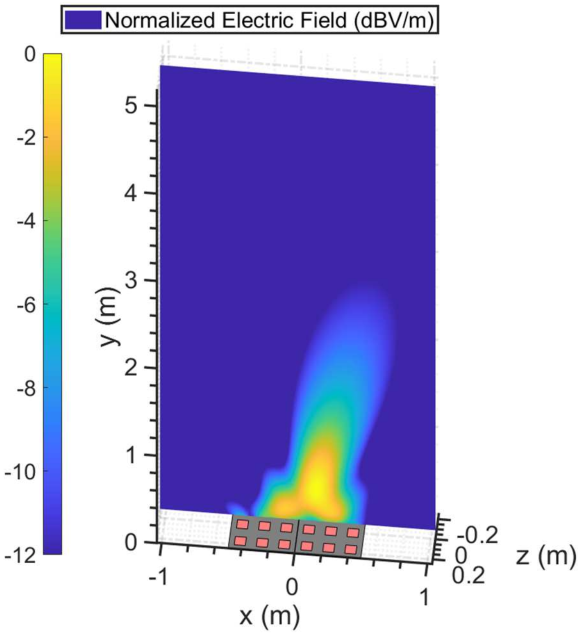


Figure 4. Normalized spatial distribution of the electric field of the NFF 6 × 3 array antenna.

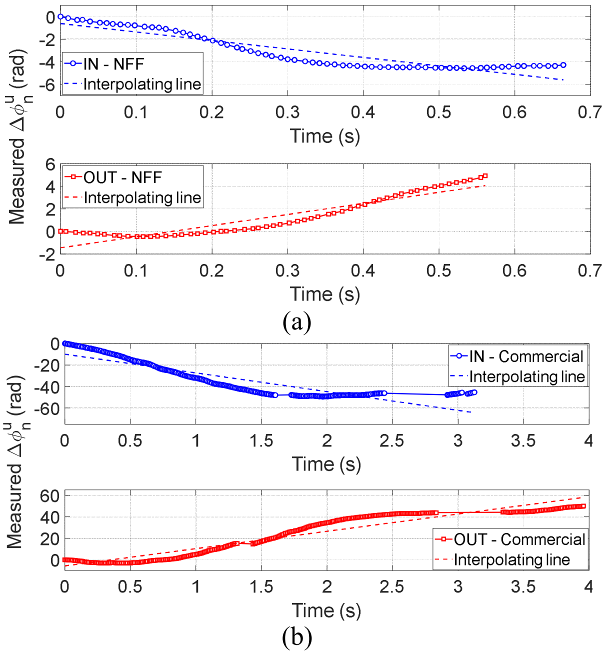


Figure 5. Measured normalized unwrapped phase sequences $\Delta\phi_n^u$ and interpolating lines for different cases: (a) *IN* (top) and *OUT* (bottom) actions measured with the NFF array; (b) *IN* (top) and *OUT* (bottom) actions measured with the commercial antenna.

3.2 Experimental results

The NFF array has been mounted at a height $h = 1.15$ m. An operator carrying a Dogbone inlay RFID tag with MZ-6 chip (-22.1 dBm sensitivity) performed a total of 48 actions, 24 of which were *IN* and 24 of which were *OUT*, at different speeds, when passing at around 1.5 m from the antenna ($y = 1.5$ m). The tag trajectory height was around 1.15 m from the floor. Measurements were gathered with an Impinj Speedway R420 UHF-RFID reader, set with a transmitting power of 20 dBm at $f_0 =$ 865.7 MHz.

The measured phase was processed to test the performance of the classification method. The same analysis with a total of 48 actions was performed when a CAEN UHF-RFID antenna with gain 8.5 dBc and HPBW=65°, tilted 30° with respect to the *y*-axis, was in the place of the NFF array.

Figure 5 shows the measured $\Delta\phi_n^u$ phase trends for two examples of *IN* and *OUT* actions, both using the NFF array and the commercial tilted FF antenna, and the respective interpolating lines used in the direction classification method. In all four cases, the slope of the interpolating line allows the right direction classification according to (4).

The commercial antenna (Figure 5b) has a larger reading zone, so it detects the tag for a longer time and consequently usually gather a higher number of tag replies. However, the measured phase presents some missed readings caused by multipath shadowing that may introduce failures in the phase unwrapping process. Above

Table 1. Confusion Matrix of the proposed Phase-Based Classification Method with the NFF array.

		PREDICTED CLASS	
		IN	***OUT***
ACTUAL CLASS	***IN***	23	1
	OUT	0	24

phenomenon is mitigated by the NFF array, for which a continuous tag detection can be observed.

The classification accuracy of the NFF array is resumed by the confusion matrix reported in Table 1. Each row of the matrix represents the actual class of the action, while each column represents the predicted (classified) class. The overall accuracy is 97.2%, which goes below 90% if the commercial antenna is used.

4 Conclusion and Future Work

This work presented a UHF-RFID smart gate equipped with a Near-Field Focused array for moving people direction classification in a RFID access control system.

A simple but effective phase-based method foresaw the employment of unwrapped phase curves gathered by a NFF array with a laterally displaced focal spot. An overall classification accuracy higher than 97% has been obtained in a real experimental setup. The NFF array allows to mitigate the multipath effect and then reduce the detection of undesired tags. An extended measurement campaign will be used to check the performance of the proposed smart RFID gate in more realistic environments, and with a larger number of persons and passages. Moreover, the method will be tested for industrial smart RFID gates adopted for monitoring of goods transit. Tests with relatively high transit speeds will be used to check the robustness of the proposed method with respect to reduction of the number of phase samples that are acquired while the tag is inside the reader antenna beam.

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6 References

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