



A Novel Low Sidelobe Level Uniform Transmit/Receive Antenna Arrays for RFID Applications

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Abstract

The presence of higher minor lobes in RFID reader antennas results in interference, while the utilization of separate antennas for transmission and reception increases the hardware cost and complexity. To address these limitations, a shared aperture antenna array with low sidelobe levels (SLLs) using a two-way array factor is presented. The proposed array utilizes uniform feeding for both the transmit and receive arrays to minimize the design feeding network complexity. The combinatorial analysis is used to turn OFF some of the receive array elements, placing its nulls with the peak SLLs of the transmit array, ensuring optimum suppression in the peak SLL of the two-way array pattern. The proposed antenna array achieves a significant improvement in SLL of about 14.9 dB at the cost of only 1.12 dB loss in the directivity compared to the conventional arrays. Furthermore, about 9 dB and 0.28 dB improvement in SLL and directivity, respectively, is observed compared to the state-of-the-art solutions.

1. Introduction

The rapid growth of the Internet of Things (IoT) demands low-cost and low-power solutions [1]-[2]. Radio Frequency Identification (RFID) printed tags and sensors are a new paradigm for IoT applications due to their low cost, negligible maintenance, and minimal power consumption. These features enable their extensive use in numerous applications such as healthcare, logistics, manufacturing, agriculture, food, etc [3]. Therefore, the effective deployment of these RFID tags in such scenarios requires a powerful RF front end (i.e., RFID reader) that can reliably receive and correctly interpret the high-frequency signals from the chipless RFID tags and sensors [4]. However, one of the major problems in the RFID reader system is interference, which will affect the detection accuracy [5]. This is primarily due to the occurrence of high sidelobes near the main radiating beam of the reader antenna [6]. Furthermore, the transmission and reception functionalities are usually obtained with two different antennas (or antenna arrays), which leads to the increased size, cost, weight, and bulkiness of the RFID reader system. One of the eminent approaches to address these limitations is to design shared aperture antenna arrays, where the transmission and reception functionalities are obtained through the same radiating aperture. Therefore, in such scenarios, the analysis of the two-way pattern is important,

which is the product of the array patterns of transmit and receive test cases [7]-[8].

The conventional approach to reduce the peak SLLs in a two-way array pattern is to apply the amplitude tapers on transmit/receive apertures. However, amplitude tapers reduce the array directivity, gain, and tapering efficiency [6]. Furthermore, they mandate a complicated feeding network design, which increases the size, cost, power consumption, etc. In [9]-[11], it is shown that aligning the transmit (or receive) array pattern peak SLL in the same position as the first null of the receive (or transmit array) can suppress the SLL in a two-way array pattern of about -31.8 dB. Furthermore, the utilization of two-weight [12]-[13], and three-weight [14]-[15] amplitude distribution can suppress the SLL below -52 dB and -57 dB, respectively. Although two/three-weight amplitude distribution significantly minimizes the peak SLLs, since the number of active elements in transceiver arrays is high, it also increases hardware system cost, complexity, and power consumption. In [16], an extended coprime receive array has been proposed to minimize the system complexity by reducing the number of active elements in the receive array. Even though the design in [16] features a number of elements in the receive array that is lower than the standard approach [11], it exhibits a SLL equal to -32 dB, which is comparable to the designs reported in [9]-[11].

This paper proposes a novel approach to further minimize the peak SLLs in a two-way array pattern using uniform transmit and thinned receive arrays. The thinning in the receive array is achieved based on combinational analysis. The proposed array accomplishes a significant improvement in peak SLL of about 14.9 dB at the cost of only 1.12 dB loss in directivity compared to the conventional arrays. Additionally, about 9 dB and 0.28 dB improvement in SLL and directivity, respectively, is observed compared to the state-of-the-art works.

2. Shared Aperture Linear Antenna Arrays

Consider a uniformly illuminated linear antenna array of N_{tx} transmitting elements, along the x -axis with inter-element separation d , as shown in Fig. 1. The corresponding normalized transmit array factor (AF_{Tx}) can be modeled as [6]:

$$AF_{Tx} = \frac{1}{N_{tx}} \sum_{n=1}^{N_{tx}} e^{-jkd(n-1)\sin\theta} \quad (1)$$

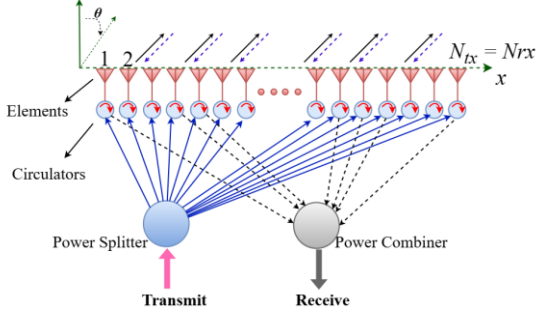


Fig. 1. The Proposed uniform transmit and thinned receive arrays.

Similarly, a linear receiving antenna array of N_{rx} elements has the following normalized receive array factor (AF_{Rx}):

$$AF_{Rx} = \frac{1}{N_{rx}} \sum_{n=1}^{N_{rx}} w_n e^{jkd(n-1)\sin\theta} \quad (2)$$

Where w_n and k are the element excitation coefficient and the wave number ($= 2\pi/\lambda$), respectively, with λ being the free space wavelength. Additionally, θ is the angle from the broadside direction. Now, using the individual array factors of transmit and receive arrays, a two-way array factor can be written as follows [11]-[13]:

$$AF_{2-way} = AF_{Tx} \times AF_{Rx} \quad (3)$$

The SLL and directivity of the two-way product pattern are the sum of standalone transmit and receive array patterns SLLs and directivity in dB [11]. For conventional uniformly excited transmitting and receiving arrays (i.e., $N_{tx} = N_{rx}$), the peak sidelobe of the two-way product pattern goes up to $-2 \times 13.26 = -26.52$ dB [12]-[13]. However, for further minimization of the SLL of a two-way array factor, the peak SLLs of the transmit (or receive) array factor must align with the nulls of the receive (or transmit) array factor. In this paper, the transmit array operates with all active elements. Conversely, the receive array is optimized, which leads to optimal placements of its nulls at the same position as the SLL of the transmit array. As a result, the peak SLL in the two-way array pattern is minimized. In the proposed approach, the receive array elements are systematically turned OFF, exploiting all possible combinations to achieve the optimal receive array. The procedure to identify the best possible combinations of ON/OFF elements in the receive array that lead to minimum peak SLL has been discussed in the following subsections.

A. Optimization Procedure

The receiving array has N_{rx} elements, and the state of each element can be determined by assigning the feeding coefficient w_n to either 0 or 1 as follows:

$$w_n = \begin{cases} 0 & \text{if element is OFF} \\ 1 & \text{if element is ON} \end{cases} \quad (4)$$

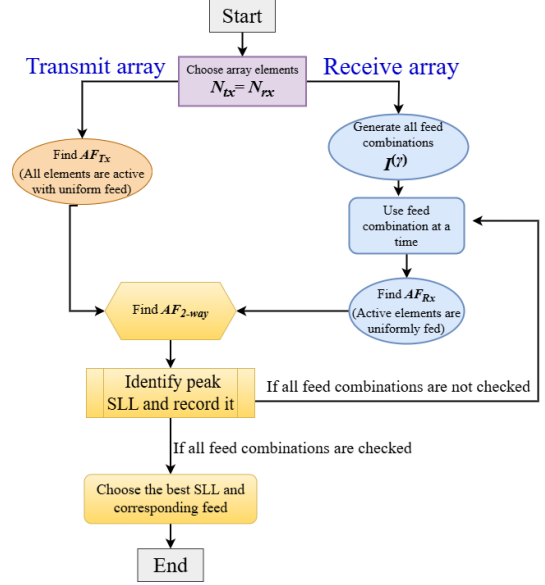


Fig. 2: The procedure for obtaining the optimal peak SLL suppression in a two-way array pattern.

Thus, there are $2^{N_{rx}}$ unique feeding combinations. The state of the n^{th} element in the γ^{th} combination can be evaluated by the following relation:

$$w_n(\gamma) = \left\lfloor \frac{\gamma}{2^{N_{rx}-n}} \right\rfloor \bmod 2 \quad (5)$$

Where $\bmod$ is the modulus operator, and $\lfloor \cdot \rfloor$ is the floor function which rounds down to the closest integer. The element index n ranges from 1 to N_{rx} , while the combination index γ is from 0 to $2^{N_{rx}}-1$. Therefore, all possible feeding combinations can be written in matrix form as follows:

$$I^{(\gamma)} = \begin{bmatrix} w_1(0) & \cdots & w_{N_{rx}}(0) \\ \vdots & \ddots & \vdots \\ w_1(2^{N_{rx}}-1) & \cdots & w_{N_{rx}}(2^{N_{rx}}-1) \end{bmatrix} \quad (6)$$

The feeding coefficients in (6) are evaluated using (5) for each combination. Furthermore, it is important to note that the first and last feed combination coefficients will be 0 and 1, respectively. The first combination (i.e., $\gamma = 0$) does not satisfy (3), while the last one (i.e., $\gamma = 2^{N_{rx}}-1$) is identical to the transmit array pattern; hence these two combinations can be ignored while finding the optimum receive array coefficients. The procedure of obtaining the optimal receive array coefficients, which leads to the minimum peak SLL of the two-way array pattern is shown in Fig. 2.

B. Illustrative examples

In this subsection, the effectiveness of the proposed design methodology discussed in Section 2A is explored by considering illustrative examples.

Example 1: Let us assume a transmit array of $N_{tx} = 15$ elements, with equal spacing at $d = \lambda/2$ along the x -axis, as

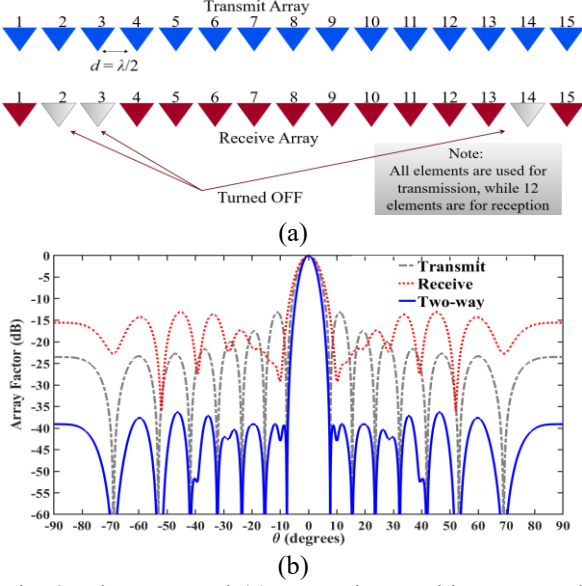


Fig. 3: The proposed (a) transceiver architecture, and (b) patterns of the transmit, receive, and two-way array factor.

shown in Fig. 3(a). When the receiving antenna array is configured with $N_{rx} = 15$ active elements, the two-way product pattern produces an SLL and directivity of about -26.27 dB and 23.52 dB, respectively. However, the SLL can be further reduced by aligning the nulls of the receive array pattern at the same location as the peak SLL of the transmit array pattern. Therefore, the optimum receive array that ensures the optimal placement of its nulls at the same positions as the transmit array peak SLL is obtained using the procedure given in Section 2A, which comprises 12 active and 3 inactive elements as shown in Fig. 3(a). This configuration achieves a two-way product pattern SLL of -36.30 dB as depicted in Fig. 3(b), which is significantly lower than -31.8 dB, and -32 dB reported in the designs [11] and [16], respectively. Additionally, the proposed array results in a directivity of 22.55 dB, exhibiting 0.97 dB loss compared to the conventional array; however, an improvement of about 0.53 dB and 0.43 dB is achieved compared to the designs proposed in [9] and [11], respectively.

Example 2: Let us consider a transmit array of $N_{tx} = 30$ elements, uniformly spaced at $d = \lambda/2$ distance along the x-axis as shown in Fig. 4(a). When the transmit and receive apertures share equal elements (i.e., $N_{tx} = N_{rx} = 30$ elements), the two-way product pattern results in a peak SLL and directivity of -26.45 dB and 29.54 dB, respectively. Instead, when the receive array is thinned using the proposed methodology, the two-way product pattern results in a peak SLL of -40.51 dB as shown in Fig. 4(b). The achieved SLL is approximately 8.71 dB, and 8.51 dB superior to the uniformly thinned [11] and extended coprime array [16], respectively.

Finally, to evaluate the efficacy of the proposed two-way array factor design approach, a linear array comprising $N_{tx} = 5$ to 35 elements has been considered, and analyzed as depicted in Fig. 5. It shows that the proposed two-way array

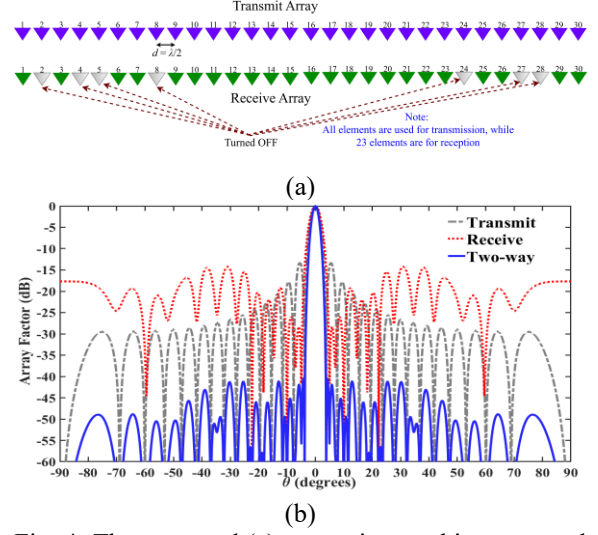


Fig. 4: The proposed (a) transceiver architecture, and (b) patterns of the transmit, receive, and two-way array factor.

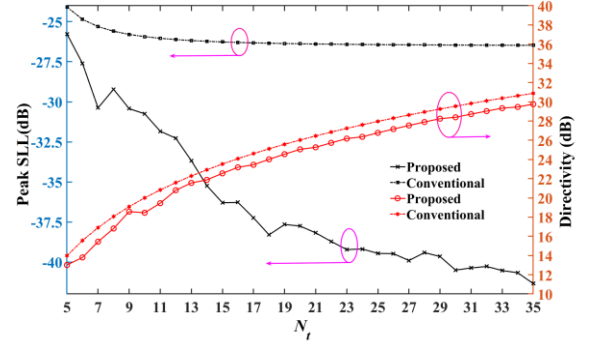


Fig. 5: The comparison of the two-way array pattern peak SLL and directivity for the proposed array with the conventional arrays.

pattern shows a superior peak SLL performance for all the elements as compared to the conventional arrays. Additionally, the peak SLL of the proposed arrays reduces with the increasing number of array elements, reaching a minimum of -41.35 dB; however, the conventional array maintains a consistent peak SLL of nearly -26.6 dB. Furthermore, the proposed array maintains a similar directivity loss of about 1.2 dB compared to conventional arrays and is expected to remain consistent for all the array sizes.

C. Figure of Merit

The overall performance of the two-way array pattern depends on achieving the minimum peak SLL with the lowest loss in directivity compared to the conventional arrays. Therefore, for a consistent design, we introduce a figure of merit (FoM) that offers the best tradeoff between the SLL achieved and the directivity loss as given by :

$$FoM = \left(\frac{|SLL|}{DL} \right)_{dB} = |SLL(dB)| - DL(dB) \quad (7)$$

TABLE-I:
Performance Comparison with State-of-the-Art works

Ref.	Feed type	Peak SLL (dB)	DL (dB)	FoM (dB)
[9]	Uniform	-31.82	1.50	30.32
[10]	Uniform	-29.20	1.30	27.90
[11]	Uniform	-31.68	1.40	30.28
[16]	Uniform	-32.26	-	-
T.W.	Uniform	-41.35	1.12	40.23

T.W.: This work; DL: Directivity loss compared to conventional arrays.

Where DL is the directivity loss in comparison with conventional arrays. The FoM ranges from 0 to ∞ , and the larger the FoM, the better the tradeoff between SLL and directivity performance. It can be noted in the designs [11]–[13] (or in Fig. 5), that the peak SLLs and directivity losses are not the same for all the elements. However, they are nearly constant for larger antenna arrays. Therefore, for a fair comparison, we have considered the SLL and directivity loss that are consistent with the larger arrays for the proposed and state-of-the-art designs and reported in Table I. It shows that the proposed array outperforms alternative solutions in [9]–[11], [16] in terms of both peak SLL and directivity loss, thus FoM. Overall, the proposed array design provides an optimal tradeoff between the peak SLL, and directivity loss, thus it is a potential candidate for RFID reader applications.

3. Conclusion

In this paper, a novel approach to lower the peak SLLs in shared aperture antenna arrays using a two-way array factor has been presented. The proposed array design shows a significant improvement in both peak SLL and directivity loss compared to the state-of-the-art works. Uniform feeding is utilized to reduce the corporate feeding network complexity. Overall, our array design approach provides an optimal tradeoff between the peak SLL, directivity loss, and hardware complexity, thus it is a potential candidate for RFID reader applications.

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