Wide-Coverage Array Antenna Using a Dual-Beam Switching for UHF RFID Applications

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***Abstract*—Based on a dual-beam switching, the wide-coverage array antenna with a 4×4 proposed matrix which generates three dual-beams is presented for the ultra high frequency (UHF) radio frequency identification (RFID) applications. The 4×4 proposed matrix generates the three dual-beams which can find the approximate location of a tag by covering the wide spatial coverage of 180°. The main beam directions can be controlled by selecting the appropriate input port of the proposed matrix. Due to the compact structure and very low reflection coefficient, the circular polarized square quadrifilar spiral antenna (QSA) array incorporated with the 4×4 proposed matrix has been configured. The fabricated array antenna operates at the 902–928 MHz band and produces three dual-beams at ±12°, ±39°, and ±68°.**

I. Introduction

In the electronics industry, it is typically desirable not only to be able to accurately track products in the production process but also to manage product lifecycles efficiently and precisely. To accurately track a product through its lifecycle, a solution that can easily record and provide information concerning the production process history is required. This may be accomplished by attaching individual identifiers on the products. Currently barcodes are the electronics industry standard for individually identifying products, but these lack the ability to record additional information. However, RFID can automatically identifies products by using a radio signal. Specifically, an RFID tag is attached to an object to be identified, and the tag communicates with an RFID reader through transmission or reception of a radio signal. In case of batteryless tag (i.e., a passive tag), a transmitted beam from the reader energizes the tag circuitry, and then the tag communicates data encoded in the tag to the reader using modulated backscatter [1]–[2].

In the conventional RFID systems, the ability of the reader to determine the location of a tag is limited because the reader typically transmits a beam with a broad pattern. Conventional RFID systems employ a reader including one or more antennas, where each antenna has a fixed beam pattern [3]–[5]. In order to provide space diversity against multi-path fading and to increase the reliability of receiving the communication from tags with unknown orientations, the conventional RFID reader antennas are typically separated by a spacing that is large compared to the transmitted beam's wavelength [6]. The maximum read range of an RFID tag is typically limited by the power needed to energize the tag and to generate the backscatter response. In addition, the read range and reliability vary significantly depending upon the scattering environment. Thus, the location of antenna element(s) for the RFID reader has to be carefully positioned and/or tuned by experts to optimize performance in settings such as, for example, a factory floor, a production facility, or a commercial establishment.

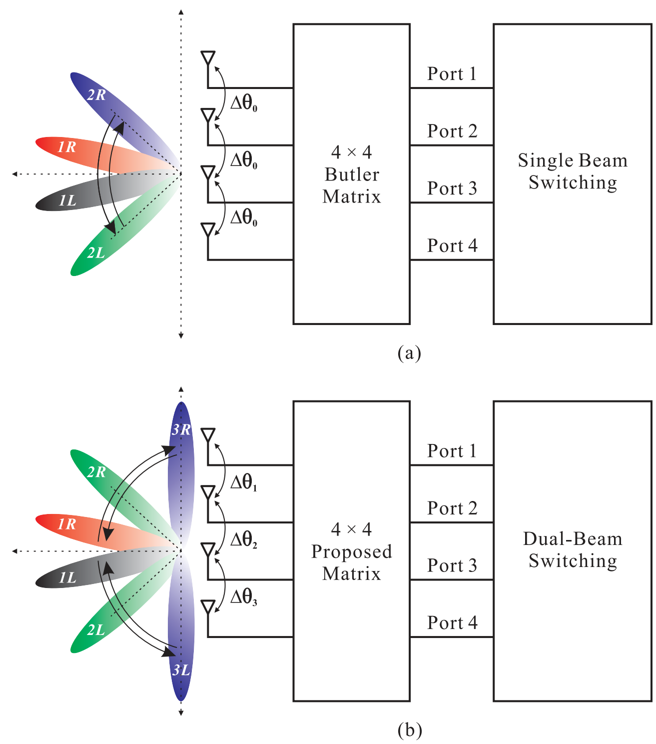


Fig. 1. The comparison of a conceptual beam switching: (a) conventional single beam switching using a 4×4 Butler matrix, (b) proposed dual-beam switching using a 4×4 proposed matrix.

To solve these problems, antenna beamforming technologies have been applied to the recent RFID systems in the UHF [7]–[11]. Antenna beamforming comprises using two or more antennas (or antenna elements) to direct electromagnetic energy to a certain region in space. Using beamforming, the direction of a beam of electromagnetic energy can be varied electronically by selecting the gains and phase of the signals fed to each of the two or more antennas. The use of a beamforming system increases the signal strength in the interrogation zone for a given transmitted power, thus allowing for either increased range for a given amount of transmitted power, or for reduction in the transmitted power required to achieve a given signal strength in the interrogation zone. In practice, the maximum radiated power (EIRP) of the reader is limited by the licensing regulations. Therefore, the benefit of an antenna array is more to reduce the transmit power of the reader rather than increasing the reading range. Due to the high cost for the implementation of analog and digital beamformings using adaptive array antenna, it is not suitable for the RFID systems although they provides several fascinating benefits such as a wide coverage, high data rate, increased capacity and flexibility [12].

For low-cost and simple implementation, the practical UHF RFID array antenna with analog beamforming networks such as a Butler matrix has been widely used [13]–[14]. Since the circuit size of the Butler matrix which consists of hybrid couplers and fixed phase shifters is bulky and impractical for a commercial RFID systems. By reducing a quadrature hybrid coupler or using a new type of coupler, a miniaturized Butler matrix in [15]–[19] were proposed and applied for the smart antenna systems. Nevertheless, the maximum beam angle of the phased array antenna with a 4×4 Butler matrix is limited within approximately $\pm 45°$ in [15] and [16].

To achieve the beamforming for a wide coverage of the interrogation zone and better and faster control of the beam using a dual-beam switching, the wide-coverage array antenna with a 4×4 proposed matrix for the UHF RFID applications is presented. This paper is organized as follows. Section II describes the array configuration for a wide coverage in detail. Design of the proposed array antenna and experimental results are presented and discussed in Section III, and a conclusion is drawn in Section IV.

II. Array Configuration for a Dual-Beam Switching

The conventional phased array antenna with a 4×4 Butler matrix generates four beams at the directions of 2L, 1L, 1R, and 2R, and the formed beams have approximately the maximum 90° spatial coverage by a single beam switching in Fig. 1(a). The phase differences ($\Delta\theta_0$) between adjacent antennas are the same values (45°, -135°, 135°, -45°) at each input port 1, 2, 3, and 4. However, due to the different phase differences ($\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$) of a 4×4 proposed matrix, three dual-beams with a theoretically 180° spatial coverage can be achieved in the proposed array antenna in Fig. 1(b). Additionally, from the dual-beam switching at the input ports, the UHF RFID reader can reduce the searching time for tags in the interrogation zone and control the angle of the switched beam by properly selecting the input port.

A. Proposed Feeding Network for a Dual-Beam

The block diagram of the conventional 4×4 Butler matrix which consists of four quadrature hybrid couplers, two fixed 45° phase shifters, and two crossovers is described in Fig. 2(a). On the other hand, the 4×4 proposed matrix consists of four quadrature hybrid couplers, four fixed phase shifters with one

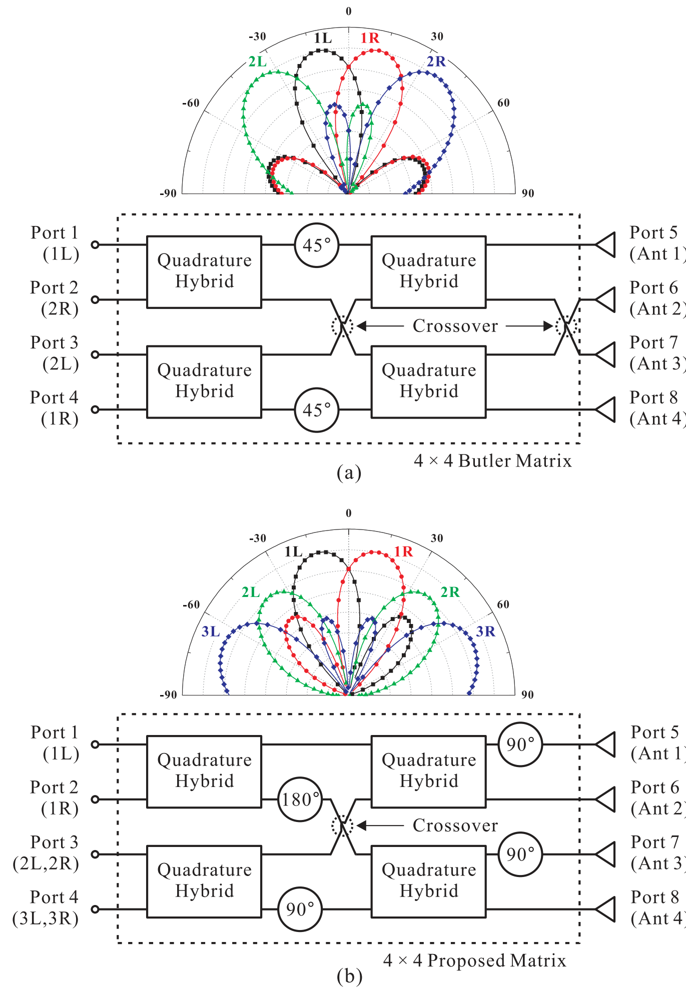
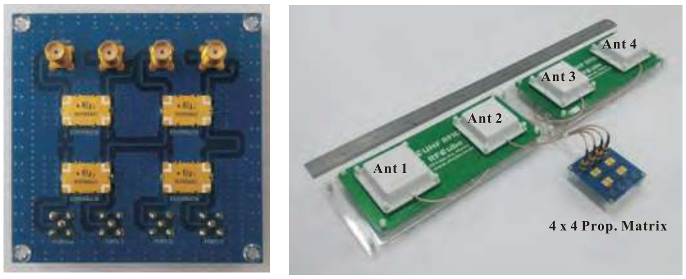


Fig. 2. Block diagram and radiation patterns of a 1×4 square QSA array at 920 MHz : (a) using a conventional 4×4 Butler matrix, (b) using a 4×4 proposed matrix which consists of four quadrature hybrid couplers, a 180° phase shifter, and three 90° phase shifters.

TABLE I
Output Phase Distributions of a 4×4 Proposed Matrix and Estimated Beam Direction with a 1×4 Circular Polarized Square QSA Array

Distributions (Unit : degree)		Input Port 1	Input Port 2	Input Port 3	Input Port 4
Output	Port 5 (Ant 1)	-90°	0°	-180°	-180°
	Port 6 (Ant 2)	-90°	0°	0°	0°
	Port 7 (Ant 3)	0°	-90°	0°	-180°
	Port 8 (Ant 4)	0°	-90°	-180°	0°
Phase Diff.	$\Delta\theta_1$	0°	0°	180°	180°
	$\Delta\theta_2$	90°	-90°	0°	-180°
	$\Delta\theta_3$	0°	0°	-180°	180°
Estimated Beam Direction		-12° (1L)	12° (1R)	±39° (2L, 2R)	±68° (3L, 3R)

180° and three 90°s, and one crossover. The phase differences



(a) (b)

Fig. 3. (a) The implementation of the proposed matrix with the commercial LTCC hybrid couplers. (b) Proposed array antenna prototype with the proposed matrix.

between the Port 6 and Port 5, between the Port 7 and the Port 6, and between the Port 8 and the Port 7 from each input port define $\Delta\theta_1$, $\Delta\theta_2$, and $\Delta\theta_3$, respectively. The phase differences at the Port 1 or 2 provide 0° and 90°, or 0° and -90°, respectively. For the dual-beam generation, the phase differences of 0° and ±180°, or ±180° have been achieved at the Port 3 or 4, respectively. From that, the parallel feed network using the 4×4 proposed matrix can be applied for the wide-coverage array antenna with three dual-beams.

B. Array Element and its Array Configuration

To cover the wide interrogation zone of a UHF RFID reader, the four-element array antenna is required. The theoretical beam directions assuming dipole antenna elements with omnidirectional radition pattern for the 4×4 butler matrix are ±15° and ±50°. On the other hand, in case of the propsoed matrix, the wide beam directions of ±12°, ±38°, and ±90° can be obtained.

Due to the attractive benefits (e.g., improved orientation diversity and reduced signal loss caused by multipath effects) of circular polarization (CP), UHF RFID reader antenna has the CP, which can be obtained by the three basic types of antennas: helix, crossed dipole, and patch. For the compact structure and excellent impedance matching, the single antenna element for the proposed array antenna utilizes the square QSA (CQA920S-6015 manufactured by RFCube co., Ltd.) with CP characteristic in [4][21]. Its operating frequency band is 902–928 MHz authorized for UHF RFID applications.

The total field of the array antenna with identical elements can be determined by the pattern multiplication (i.e., the product of the field of a single element and the array factor (AF) of that array). The AF of a linear array with equally spaced N radiating elements placed along horizontal axis x as a function of the polar angle (θ) can be expressed by

$$AF_{\text{linear}}(\theta) = \sum_{n=1}^{N} I_n \cdot e^{j\cdot(\delta_n + k\cdot d\cdot n\cdot sin\theta)} \tag{1}$$

where I_n and $\delta_n (n = 1, 2, \ldots, N)$ are the amplitude and phase excitation of nth array element, and d and k are the distance between two adjacent elements and the wave number, respectively.

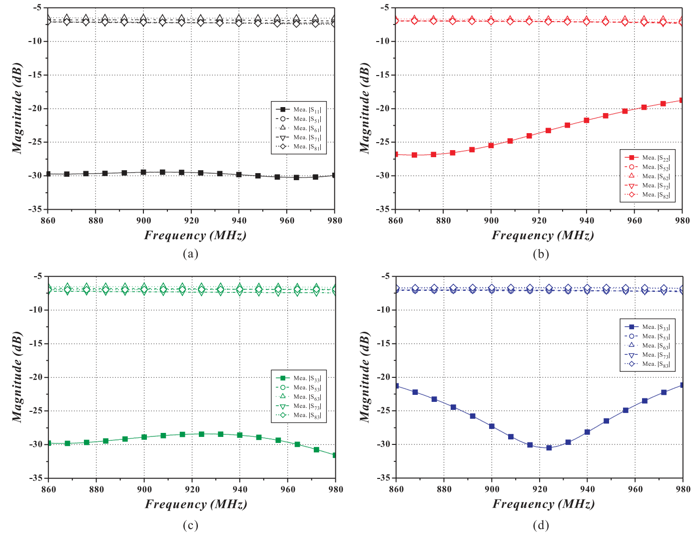


Fig. 4. Measured input reflection coefficient and output power distributions of a 4×4 proposed matrix when the signal is fed at (a) Port 1, (b) Port 2, (c) Port 3, (d) Port 4. The occupied symbol represents the reflection coefficient at the input port, and the vacant symbols such as a circle (◯), triangle (△), inverted triangle (▽), and diamond (◇) describe output power of the Ports 5–8, respectively.

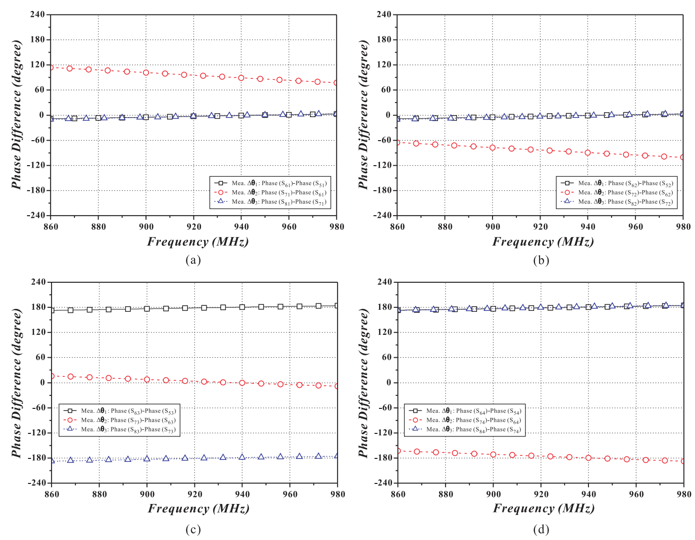


Fig. 5. Measured phase differences of a 4×4 proposed matrix when the signal is fed at (a) Port 1, (b) Port 2, (c) Port 3, (d) Port 4. The square (□), circular (◯), and triangular (△) symbols represent the phase differences($\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$) between the Port 6 and Port 5, between the Port 7 and the Port 6, and between the Port 8 and the Port 7 from each input port, respectively.

The calculated radiation patterns of the 1×4 square QSA array antenna with a 4×4 Butler matrix at $d = \lambda/2$ (λ is the wavelength at the operating frequency) are shown in Fig. 2(a). Due to the wide beamwidth of the square QSA, the maximum beam directions (2L and 2R) of the 1×4 square QSA array with the Butler matrix are approximately 38°. On the other hand, in case of the proposed square QSA array with a 4×4 proposed matrix, the maximum beam directions (3L and 3R) are approximately 68° which is the twice wider than that of a square QSA array with the Butler matrix in Table I. It means that the proposed array antenna with the proposed matrix can expand the interrogation zone compared to the conventional Butler matrix.

III. Results and Discussion

To demonstrate the proposed wide-coverage 1×4 square QSA array with the 4×4 proposed matrix for UHF RFID applications, the implementation and experimental verification are described in this Section.

A. Proposed Array Antenna Using a 4×4 Proposed Matrix

The 4×4 proposed matrix incorporated with the four commercial low loss LTCC hybrid couplers, RCP890A03 manufactured by RN2 Technologies co., Ltd. [20], is designed and fabricated on a glass epoxy three-layer FR4 PCB subtsrate (($\epsilon_r = 4.4$, tan $\delta = 0.02$, substrate thickness $t_{sub} = 0.8$ mm with 0.4 mm thickness between the layers) with a copper thickness of t = 35 μm. The commercial LTCC hybrid couplers has the maximum 0.15 dB of insertion loss, ±0.15 dB of amplitude balance, and ±2° of phase at the operating frequency, 815–960 MHz.

Fig. 3(a) shows the implementation of the proposed matrix. Four phase shifters are designed by the microstrip line and one crossover is easily achieved by a multilayer configuration. Using the proposed matrix, four square QSAs with the equal distance (160 mm, approximately $\lambda/2$ at 920 MHz) are linearly deployed along the horizontal axis in Fig. 3(b). The sizes of the 4×4 proposed matrix and array antenna are 75×75 mm^2 and 560×110 mm^2, respectively.

Using a two-port vector network analyzer, the scattering parameters of the 4×4 proposed matrix are measured when the unused ports are properly 50 ohm terminated. The measured magnitude and phase differences of the proposed matrix are shown in Figs. 4 and 5 when the signal is fed at each port. Within the operating frequency band, 902–928 MHz, the maximum amplitude imbalances are less than 1 dB at the whole ports. Additionally, the input reflection coefficients of the proposed matrix are less than -20 dB, which represents excellent impedance matching at each input port. The measured insertion loss has an 7.2 dB loss including the theoretical 6 dB power distribution loss and the losses from LTCC couplers and multilayer implementation (i.e., signal using a via) at the operating frequency of 902–928 MHz. Compared to the phase differences ($\Delta\theta_1$, $\Delta\theta_2$, and $\Delta\theta_3$) in Table. I, the maximum phase error has less than ±6° at the operating frequency.

Fig. 6 shows the measured reflection coefficient for a single antenna element and a 1×4 square QSA array with the proposed matrix for a wide coverage. Due to the excellent impedance matching characteristic of the single antenna element and the proposed matrix, the reflection coefficient of the proposed array antenna is less than -15 dB regardless of the input ports.

The square QSA element has a measured peak gain of approximately 2.5 dBic at 920 MHz [4]. The gains of the proposed square QSA array using a 4×4 proposed matrix for

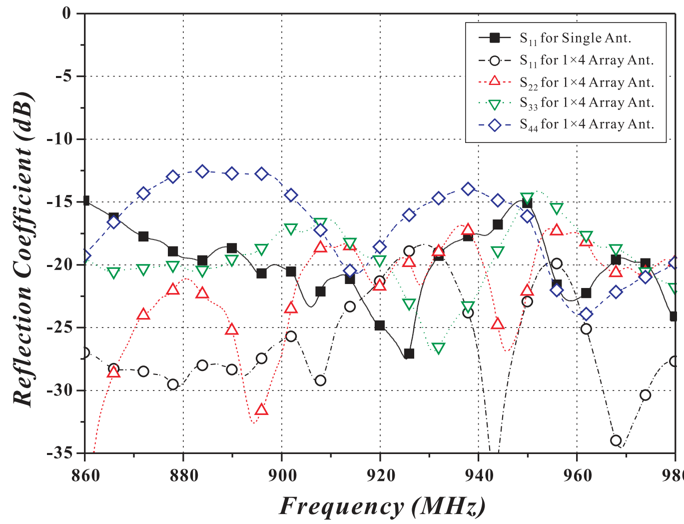


Fig. 6. Measured reflection coefficient for a single antenna element and a 1×4 square QSA array with the proposed matrix for a wide coverage.

each input are ±7.3 dBic at the Ports 1 and 2, ±5.0 dBic at Port 3, and ±5.6 dBic at Port 4. Since the radiation patterns at Ports 3 and 4 exhibit dual beams, the peak gains at Ports 3 and 4 are slightly reduced as compared to single beam patterns at Ports 1 and 2.

B. Experimental Verification for a Wide Coverage

The experiments are conducted inside an anechoic chamber to correctly measure the tag identification and corresponding beam pattern characteristics without any multipath effects. Fig. 7 shows RFID tag identification setup for the wide coverage using a commercial UHF RFID reader (ALR-9900+ by Alien Technology) with the proposed array antenna and RFID tags (ALN-9640 by Alien Technology). The distance (d) between the RFID reader and tags, the height (h) from the ground plane, and the spacing (s) between tags is approximately 2.5 m, 1.3 m, 0.15 m, respectively.

For the CP characteristic, the tags are attached respectively with the 45° tilted angle on the paperboard fence with the 1 mm thickness. For the performance evaluation of a wide coverage characteristic, the fence which has the same distance (d) away from the 1×4 proposed array antenna is divided into seven sectors from (A) to (F), which covers 180° of the front in Fig. 7. The total number of the installed tags is 35, and the tags are encoded with an individual ID number. The height of the proposed array antenna is fixed on h from the ground plane which is the same to the height of tags. Its setup verifies the identification of all tags using the commercial UHF RFID reader with the 1×4 square QSA array and the proposed matrix by switching the all ports.

To compare the performance evaluation for the widespread tags, tag identification for the 1×4 square QSA array with the direct feed are shown in Fig. 8 when the signal of 27 dBm at the operating frequency is fed by the each port. Due to the influence of the antenna coupling, tag identification depends on the position of the antenna element. However, in case of

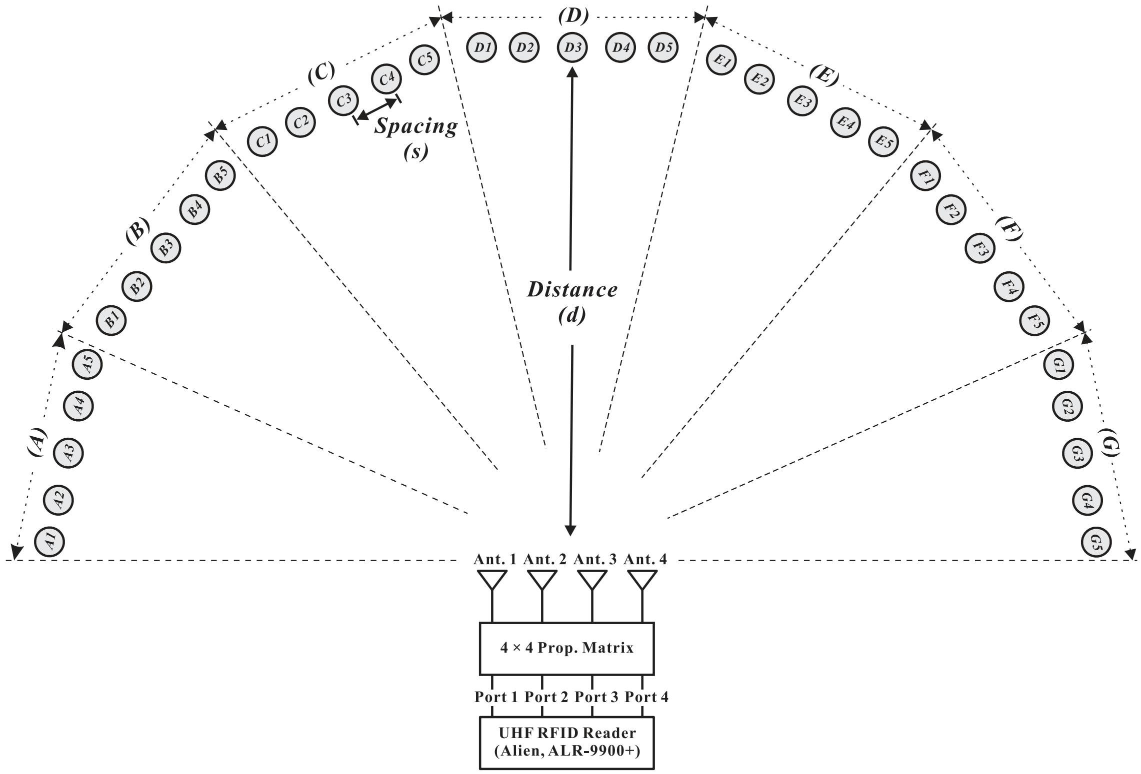


Fig. 7. Tag identification setup for the wide coverage using a commercial UHF RFID reader (ALR-9900+ by Alien Technology) with the proposed array antenna and RFID tags (ALN-9640 by Alien Technology) . The distance (d) between the RFID reader and tags, the height (h) from the ground plane, and the spacing (s) between tags is approximately 2.5 m, 1.3 m, 0.15 m, respectively.

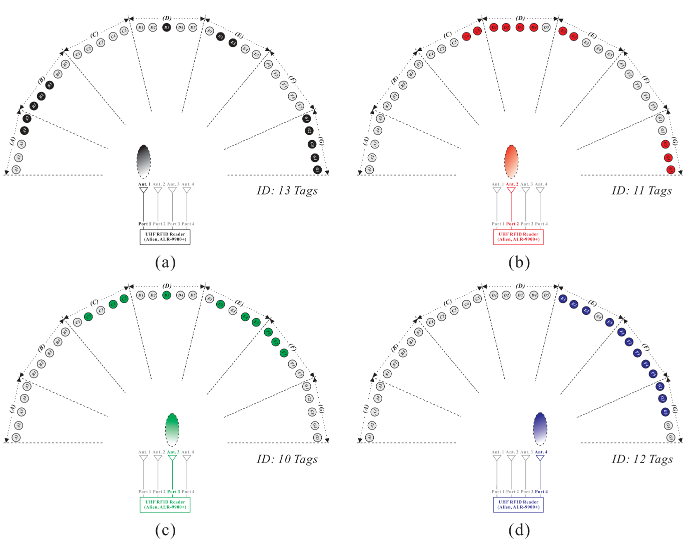


Fig. 8. Measured tag identification of a 1×4 square QSA array with the direct feed with regard to the switching of input ports: (a) Port 1, (b) Port 2, (c) Port 3, and (d) Port 4.

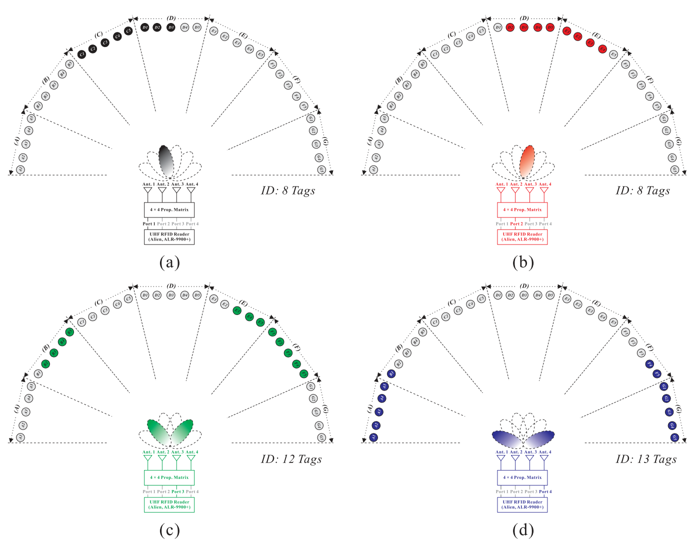
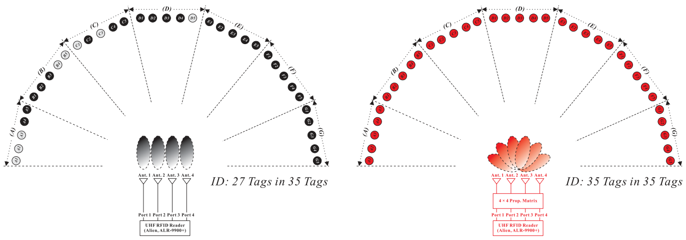


Fig. 9. Measured tag identification of a 1×4 square QSA array with the proposed matrix with regard to the switching of input ports: (a) Port 1, (b) Port 2, (c) Port 3, and (d) Port 4.

the 1×4 proposed matrix, tag identification can be achieved with dual interrogation zones without the interference between antenna elements in Fig. 9.

Fig. 10 shows the comparison results to the measured tag identification of the 1×4 square QSA array with regard to the all port switching with the direct feed or the proposed matrix. Since the tag identification in the square QSA array with the direct feed is overlapping between the ports, the total number of the recognized tags is 27, and the recognition rate of approximately 77% has been obtained. On the other hand,



(a) (b)

Fig. 10. Comparison to the measured tag identification of the 1×4 square QSA array with regard to the all port switching: (a) with the direct feed and (b) with the proposed matrix.

the proposed antenna has been 100% of the recognition rate in the widespread 35 tags.

IV. Conclusion

In this paper, a wide-coverage array antenna incorporated with the 4×4 proposed matrix has been proposed and demonstrated. The 4×4 proposed matrix generates the three dual-beams which can cover the wide spatial coverage of 180°. The main beam directions can be controlled by selecting the appropriate input port of the proposed matrix. For the UHF RFID reader antenna array with the circular polarization, the square quadlifilar spiral antenna array with compact structure and excellent impedance matching has been applied. The fabricated array antenna operates at the 902–928 MHz band and produces three dual-beams at $\pm 12°$, $\pm 39°$, and $\pm 68°$. By switching the dual beams, the UHF RFID reader using the proposed 1×4 square QSA array can achieve the wide-coverage interrogation zone. Additionally, it is very helpful for the reader to find the tag location because the reader using the proposed antenna array can be possible to control the beam directions according to the port selection.

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