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Research Article

Quadruple-feed beam-controlled antenna array for the localisations of ultra-high-frequency radio-frequency identification tags

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Abstract: Item-level tagging has been required to the retail market with densely placed items as well as the production line. Owing to the multi-path fading, the blind spots where the tag is non-responsive can be created. Furthermore, in case of the indoor radio-frequency identification (RFID) localisation system, additional circuits and localisation algorithms are indispensable for accurate localisation of RFID tags. In this study, in order to solve this problem, the beam-controlled antenna array with a quadruple beamforming network which generates multiple beams is presented for ultra-high-frequency (UHF) RFID systems. The proposed quadruple-feed antenna array can cover the wide spatial coverage, and the main beam directions of the proposed array can be controlled by selecting the appropriate input port of the quadruple network. The fabricated antenna array with the quadruple-feed network operates at the 902–928 MHz band and produces scannable multiple beams for UHF RFID localisation system within the wide interrogation zone.

1 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, radio-frequency identification (RFID) can automatically identify products 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 energises the tag circuitry, and then the tag communicates data encoded in the tag to the reader using modulated backscatter [1–3].

The ability of the reader to determine the location of a tag in conventional RFID systems 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 [4–9]. 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 with the antenna wavelength [10]. Moreover, for a long range and effectively error-free RFID identification, Sabesan *et al.* [11] proposed the distributed antenna system using antenna diversity combined with phase and frequency hopping. To dynamically control the dead zones, the RF processing unit for various frequency and phase hopping configurations has been required. The maximum read range of an RFID tag is typically limited by the power needed to energise the tag and to generate the backscatter response. In addition, the read range and reliability vary significantly depending on the scattering environment [12]. Thus, the location of antenna element(s) for the RFID reader has to be carefully positioned and/or tuned by experts to optimise performance in settings such as, for example, a factory floor, a production facility or a commercial establishment. Particularly, in case of the item-level tagging at the retail market with densely placed items, the dead zones (or blind spots) where the tag is non-responsive can be created because of the multi-path fading [13, 14]. Furthermore, the indoor RFID localisation system can compute accurate localisation of the scattered RFID tags based on phase difference [15], a zero-phase-shift line [16] or received signal strength [17]. However, additional circuits and localisation algorithms are indispensable for accurate localisation of RFID tags.

To solve these problems, antenna beamforming technologies have been applied to the recent RFID systems in the ultra-high frequency (UHF) [18–24]. Antenna beamforming comprises using two or more antenna elements to direct electromagnetic energy to a certain region in space. Using beamforming technologies, 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 (i.e. effective isotropic radiated power) 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. Recently, using the microstrip patch antenna array in the near-zone, the uniform field distribution within a target zone (<0.5 m $\times$ 0.5 m) is achieved [24].

Owing the high cost for the implementation of analogue and digital beamformings using adaptive array antenna, it is not suitable for the RFID systems although they provide several fascinating benefits such as a wide coverage, high data rate, increased capacity and flexibility [25]. For low-cost and simple implementation, the practical UHF RFID array antenna with analogue beamforming networks such as a Butler matrix has been widely used [26–28]. Since the circuit size of the Butler matrix which consists of hybrid couplers and fixed phase shifters is bulky and impractical for the commercial RFID systems. By reducing a

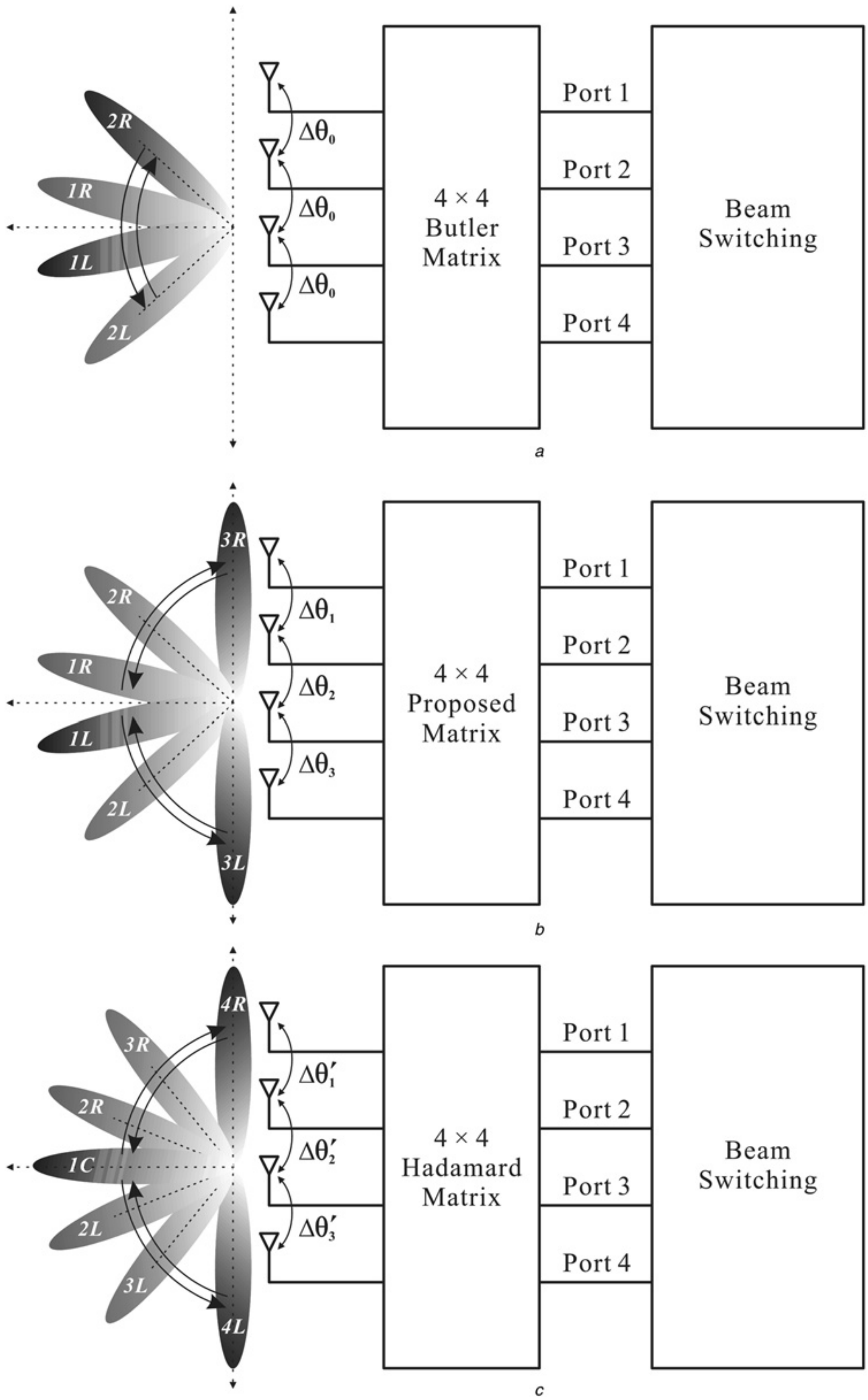

Fig. 1 *Comparison of a conceptual beam switching*

a Conventional beam switching using a 4 × 4 Butler matrix
b Proposed beam switching using a 4 × 4 proposed matrix
c Proposed beam switching using a 4 × 4 Hadamard matrix

quadrature hybrid coupler or using a new type of coupler, a miniaturised Butler matrix in [29–32] was 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 ∼ ± 49° in Fig. 1*a*. Owing to the beam splitting characteristics, the switched array antenna with a Hadamard matrix feed is introduced in [33].

In this paper, to achieve the wide coverage of the interrogation zone and better and faster control of the beam switching, the quadruple-feed beam-controlled antenna array with a proposed matrix or a 4 × 4 Hadamard matrix for the UHF RFID localisation applications is presented in Figs. 1*b* and *c*. This paper is organised as follows. Section 2 describes the multiple beam switched array configuration for a wide coverage in detail. Design of the proposed

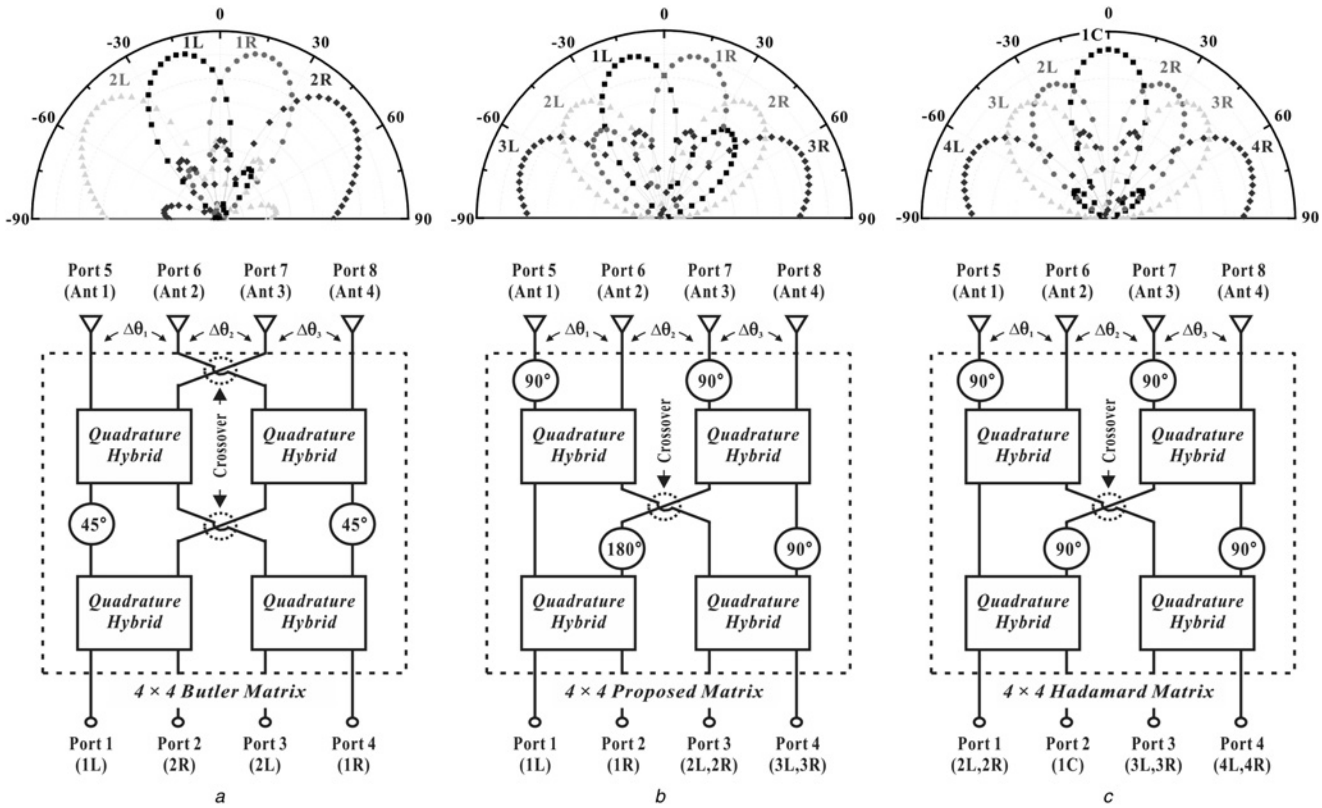

Fig. 2 *Block diagram and beam directions of a quadruple-feed antenna array*

a Conventional 4 × 4 Butler matrix
b Quadruple-feed matrix which consists of four quadrature hybrid couplers, a 180° phase shifter and three 90° phase shifters
c Hadamard quadruple matrix which consists of four quadrature hybrid couplers and four 90° phase shifters

array antenna and experimental results are presented and discussed in Section 3, and a conclusion is drawn in Section 4.

2 Array configuration for a multi-beam switching

For the switched beam generation, the switched array antenna is fed by a 4-port beamforming network. According to the magnitude and phase differences of each input port, the multi-beam at the antenna array is determined.

2.1 Beamforming network for multiple beams

Fig. 2 shows the block diagram and radiation patterns of a quadruple-feed antenna array at 915 MHz. In case of a Butler matrix feeding network, it consists of four quadrature hybrid couplers, two fixed 45° phase shifters and two cross-overs described in Fig. 2*a*. On the other hand, the 4 × 4 proposed or Hadamard matrix consists of four quadrature hybrid couplers, four fixed phase shifters with one 180° and three 90°s or four 90°s, and one cross-over in Figs. 2*b* and *c*. When the phase differences 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 defined $\Delta\theta_1$, $\Delta\theta_2$ and $\Delta\theta_3$, respectively, the phase differences ($\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$) between adjacent antennas in a Butler matrix are the same values (−45°, 135°, −135°, 45°) at each input ports 1, 2, 3 and 4 in Table 2, respectively. The switched array antenna with a 4 × 4 Butler matrix generates four beams at the directions of 1 L, 2R, 2L and 1R, and the formed beams have ∼90° spatial coverage by a single-beam switching in Fig. 2*a*.

However, because of the different phase differences ($\Delta\theta_1$, $\Delta\theta_2$, $\Delta\theta_3$) of a 4 × 4 proposed or Hadamard matrix, three dual-beams or a single-beam and three dual-beams with a wide spatial coverage can be achieved in the proposed array antenna in Figs. 2*b* and *c*. Owing to the different phase shifters between the proposed or Hadamard matrix, the generated beams in the input ports 1 and 2 are different in the middle of the beam coverage. In particular, the beams of the antenna array with the proposed matrix have nearly uniform azimuthal beamwidths (∼30°) at each input port because the phase differences between the adjacent antenna ports are <90° in Table 1. It is effective to detect the scattered tags without overlapping tag identification. On the other hand, the beams (2L, 2R) of the antenna array with the Hardamard matrix are overlapped with other neighbouring beams (1C, 3L, 3R).

From the beam switching at the input ports, the UHF RFID reader can reduce the searching time for tags in the interrogation zones and control the angle of the switched beam by properly selecting the input port. Moreover, for the dual-beam generation, the phase differences of 0° and ± 180°, or ± 180° have been achieved. From that, the parallel feed network using the 4 × 4 proposed or Hadamard matrix can be applied for the wide beam directional

Table 1 Comparisons with antenna system for UHF RFID identifications

References	Antenna elements	Distance	Simplicity for installation	Multi-path fading	Design cost	Coverage
[5]	1	far-field	high	sensitive	very low	medium
[11]	8 (Tx: 4, Rx: 4)	far-field	low	insensitive	very high	wide
[16]	4	near-field	high	–	medium	–
[24]	13 × 13	far-field	medium	sensitive	medium	narrow
Proposed	1 × 4	far-field	high	insensitive	low	wide

Table 2 Output phase distributions of the estimated beam directions with the quadruple-feed beam-controlled antenna array (unit: degree)

Input	Port	Output				Phase difference			Estimated beam directions
		Port 5	Port 6	Port 7	Port 8	$\Delta\theta_1$	$\Delta\theta_2$	$\Delta\theta_3$	
Butler matrix	port 1	−45°	−90°	−135°	−180°	−45°	−45°	−45°	−15° (1L)
	port 2	−135°	0°	−225°	−90°	135°	135°	135°	49° (2R)
	port 3	−90°	−225°	0°	−135°	−135°	−135°	−135°	−49° (2L)
	port 4	−180°	−135°	−90°	−45°	45°	45°	45°	15° (1R)
proposed matrix	port 1	−90°	−90°	0°	0°	0°	90°	0°	−12° (1L)
	port 2	0°	0°	−90°	−90°	0°	−90°	0°	12° (1R)
	port 3	−180°	0°	0°	−180°	180°	0°	−180°	±39° (2L, 2R)
	port 4	−180°	0°	−180°	0°	180°	−180°	180°	±68° (3L, 3R)
Hadamard matrix	port 1	0°	0°	−180°	−180°	0°	−180°	0°	±24° (2L, 2R)
	port 2	0°	0°	0°	0°	0°	0°	0°	0° (1C)
	port 3	−180°	0°	0°	−180°	180°	0°	−180°	±39° (3L, 3R)
	port 4	−180°	0°	−180°	0°	180°	−180°	180°	±68° (4L, 4R)

array antenna with multiple beams such as a single-beam and three dual-beams.

2.2 Antenna 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 radiation pattern for the 4×4 Butler matrix are $\pm 14°$ and $\pm 49°$. On the other hand, in case of the proposed matrix, the wide beam directions of $\pm 12°$, $\pm 38°$ and $\pm 90°$ can be obtained.

Owing to the attractive benefits (e.g. improved orientation diversity and reduced signal loss caused by multi-path effects) of circular polarisation (CP), UHF RFID reader antenna has the CP, which can be obtained by the three basic types of antennas: helix,

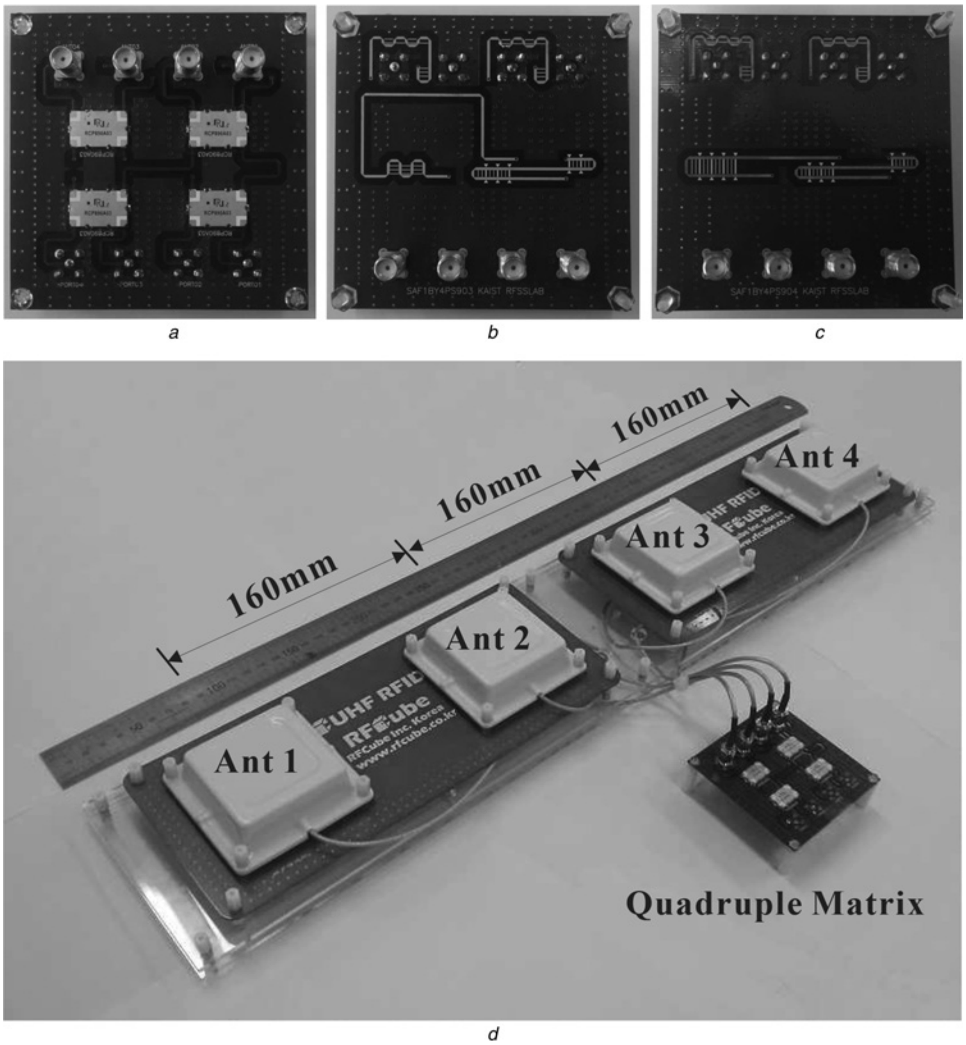

Fig. 3 *Implementation of the designed quadruple beamforming feeding network and the proposed antenna array*

a Front view of the designed proposed or Hadamard quadruple matrix
b Back view of the proposed quadruple matrix
c Back view of the Hadamard quadruple matrix
d Antenna array prototype with the quadruple-feeding network

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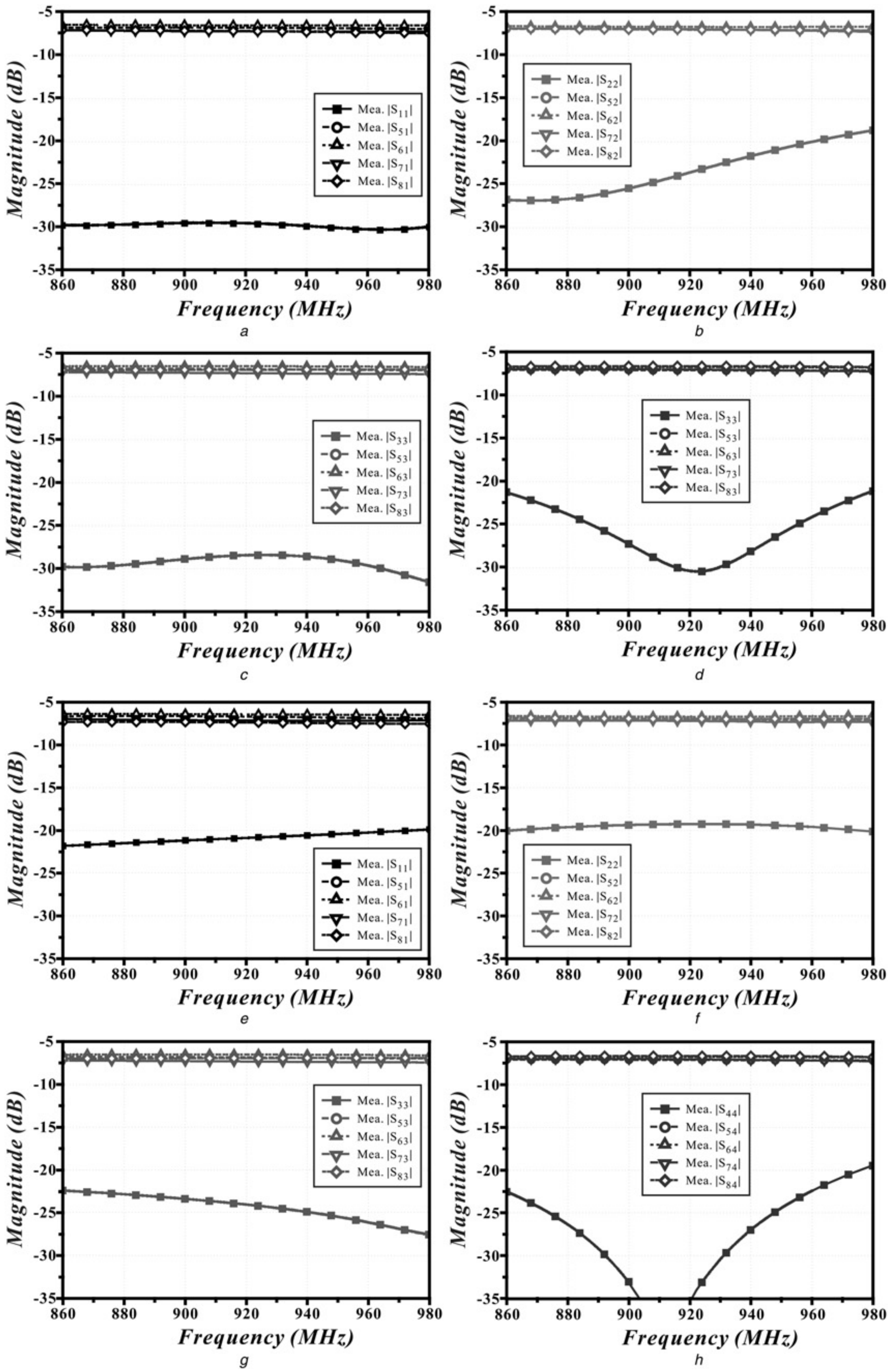

Fig. 4 *Measured input reflection coefficient and output power distributions*

a–d Port 1–Port 4 of a proposed matrix
e–h Port 1–Port 4 of a Hadamard matrix

crossed dipole and patch. As an antenna element for the proposed array, the circularly polarised square quadrifilar spiral antenna (QSA) is utilised [6]. The QSA, which consists of four spiral antennas with equal amplitude and quadrature phases, has a compact structure and excellent impedance matching characteristic. Its operating frequency band is 902–928 MHz authorised for UHF RFID applications.

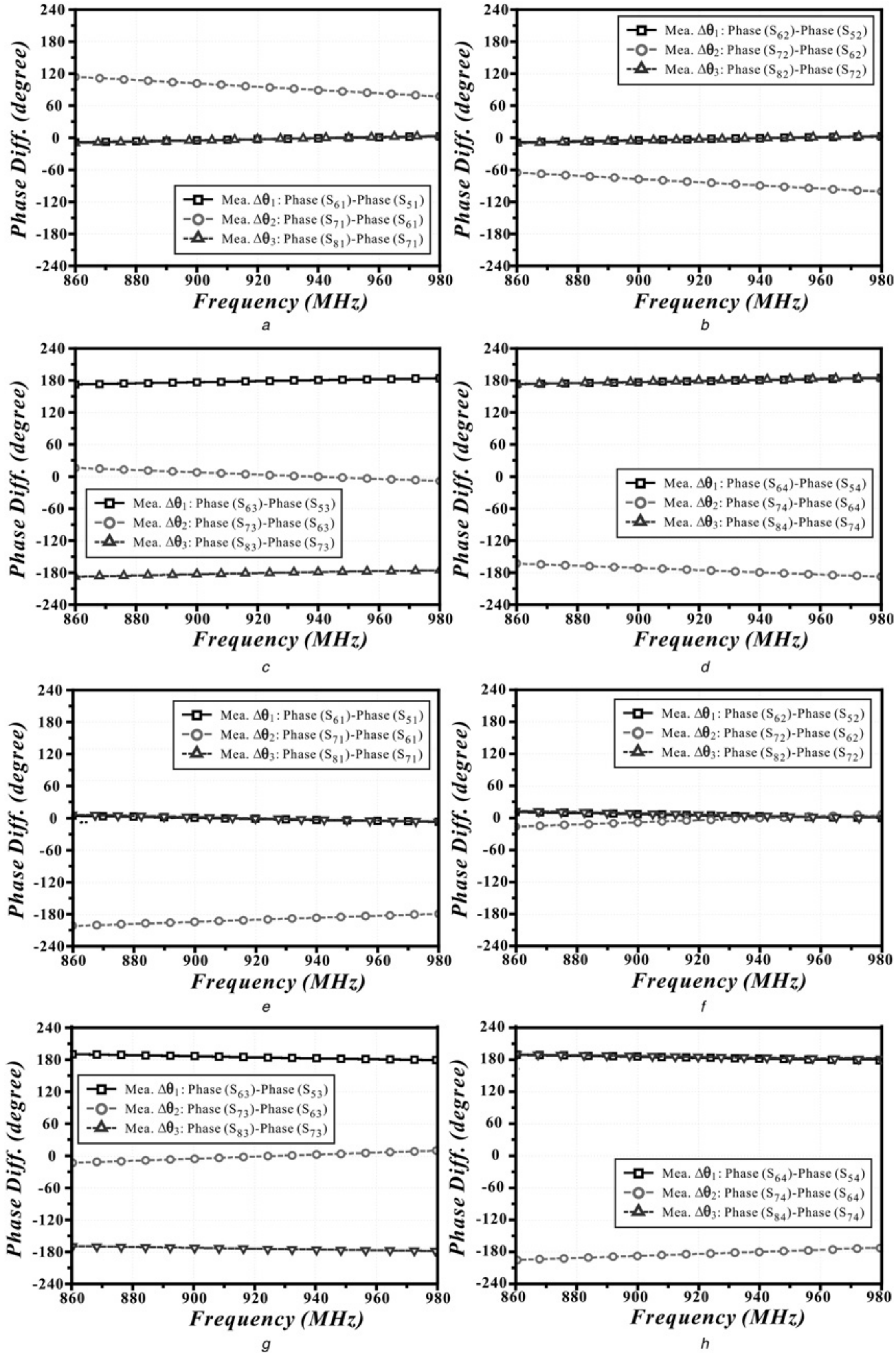

Fig. 5 *Measured phase differences*

a–d Port 1–Port 4 of a proposed matrix
e–h Port 1–Port 4 of a Hadamard matrix

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 x-axis as a function of the polar angle (θ) can be expressed by

$$\mathrm{AF}_{\mathrm{linear}}(\theta) = \sum_{n=1}^{N} I_n \mathrm{e}^{\mathrm{j}\cdot(\delta_n + kdn \sin\theta)} \tag{1}$$

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

The calculated radiation patterns of the 1×4 square QSA array with a 4×4 Butler matrix at $d = \lambda/2$ (λ is the wavelength at the operating frequency) are shown in Fig. 2*a*. Owing 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 $\sim 49°$. On the other hand, in case of the proposed square QSA array with a 4×4 proposed or Hadamard matrix, the maximum beam directions (3L and 3R) are $\sim 68°$ which is much wider than that of a square QSA array with the Butler matrix in Table 2. It means that the proposed multi-beam switched array antenna with the proposed or Hadamard matrix can expand the interrogation zone compared with the conventional Butler matrix.

3 Results and discussion

To demonstrate the beam-controlled antenna array with the quadruple feeds such as the 4×4 proposed or Hadamard matrix for the localisations of UHF RFID tags, the implementation and experimental verification are described in this section.

3.1 Proposed array antenna using a 4 × 4 beamforming network

The 4×4 beamforming matrix incorporated with the four commercial low-loss low temperature co-fired ceramics (LTCC) hybrid couplers, RCP890A03 manufactured by RN2 Technologies co., Ltd. [34], is designed and fabricated on a glass epoxy three-layer FR4 printed circuit board substrate (($\varepsilon_r = 4.4$, tan $\delta = 0.02$, substrate thickness $t_{\mathrm{sub}} = 0.8$ mm with 0.4 mm thickness between the layers) with a copper thickness of $t = 35$ µm. The commercial LTCC hybrid couplers have 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.

Figs. 3*a–c* show the implementation of the designed proposed or Hadamard matrix. Fixed phase shifters are designed by the microstrip line and one cross-over is easily achieved by a multilayer configuration. Using the designed proposed or Hadamard matrix, four square QSAs with equal distance (160 mm, ∼$\lambda/2$ at the 915 MHz) are linearly deployed along the horizontal axis in Fig. 3*d*. The sizes of the 4×4 beamforming network, an antenna element and array antenna are $75(W) \times 75(L)$ mm^2, $60(W) \times 60(L) \times 20(H)$ mm^3 and $560(W) \times 110(L) \times 20(H)$ mm^3, respectively.

Using a two-port vector network analyser, the scattering parameters of the designed 4×4 proposed or Hadamard matrix are measured when the unused ports are properly 50 Ω terminated. The measured magnitude and phase differences of the proposed or Hadamard 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 <1 dB at the whole ports. Additionally, the input reflection coefficients of the designed matrix are less than approximately −20 dB, which represents excellent impedance matching at each input port. The measured maximum insertion loss in the operating frequency band of 902–928 MHz has a 7.4 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). Compared with the phase differences ($\Delta\theta_1$, $\Delta\theta_2$ and $\Delta\theta_3$) in Table 2, the maximum phase error has <± 10° in the operating frequency band.

Fig. 6 shows the measured reflection coefficient for a single antenna element and a 1×4 square QSA array with the designed Hadamard matrix for a wide coverage. Owing to the excellent impedance matching characteristic of the single antenna element and the designed matrix, the reflection coefficient of the proposed array antenna is <−15 dB regardless of the input ports. Fig. 7 shows the simulated and measured peak gains with regard to the frequency.

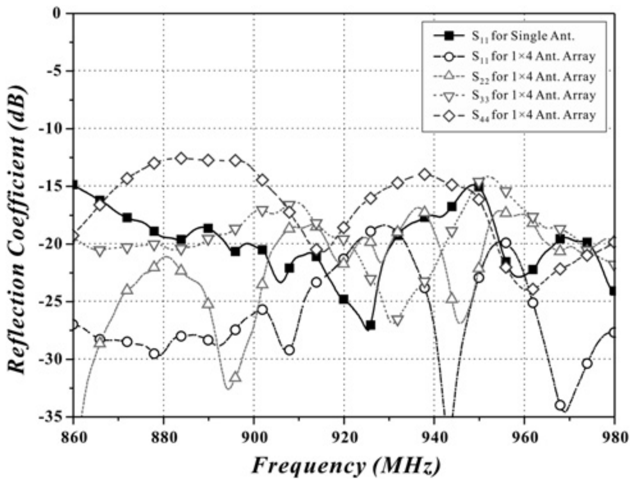

Fig. 6 *Measured reflection coefficient for a single antenna element and a 1 × 4 antenna array with the designed Hadamard matrix*

According to the design proposed or Hadamard matrix beamforming network, the simulated and measured radiation patterns of the proposed antenna array with regard to the input ports in *xz*-plane at the centre frequency (915 MHz) are plotted in Fig. 8, respectively. Owing to the feed network characteristic, the maximum peak angle of 68° in the proposed antenna array is obtained. Compared with the single antenna element, the proposed antenna array indicates that the wide-coverage reading range for UHF RFID applications can be achieved.

3.2 Experimental verification for wide beam directions

The experiments are conducted inside an anechoic chamber to correctly measure the tag identification and corresponding beam pattern characteristics without any multi-path effects in Figs. 9 and 10. Fig. 10 shows RFID tag identification setup for the wide coverage using a commercial UHF RFID reader (ALR-9900 + by Alien Technology which can access a four-port antenna with an automatic port control function) 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 ∼2.5, 1.3 and

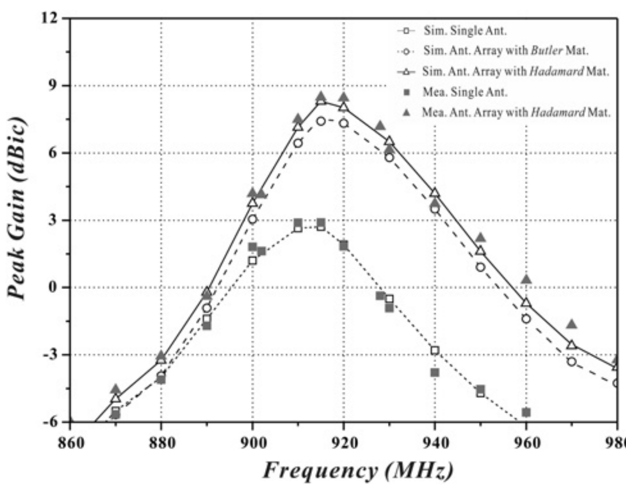

Fig. 7 *Simulated and measured peak gains of the antenna element and the proposed antenna array with the designed Hadamard matrix as a function of frequency*

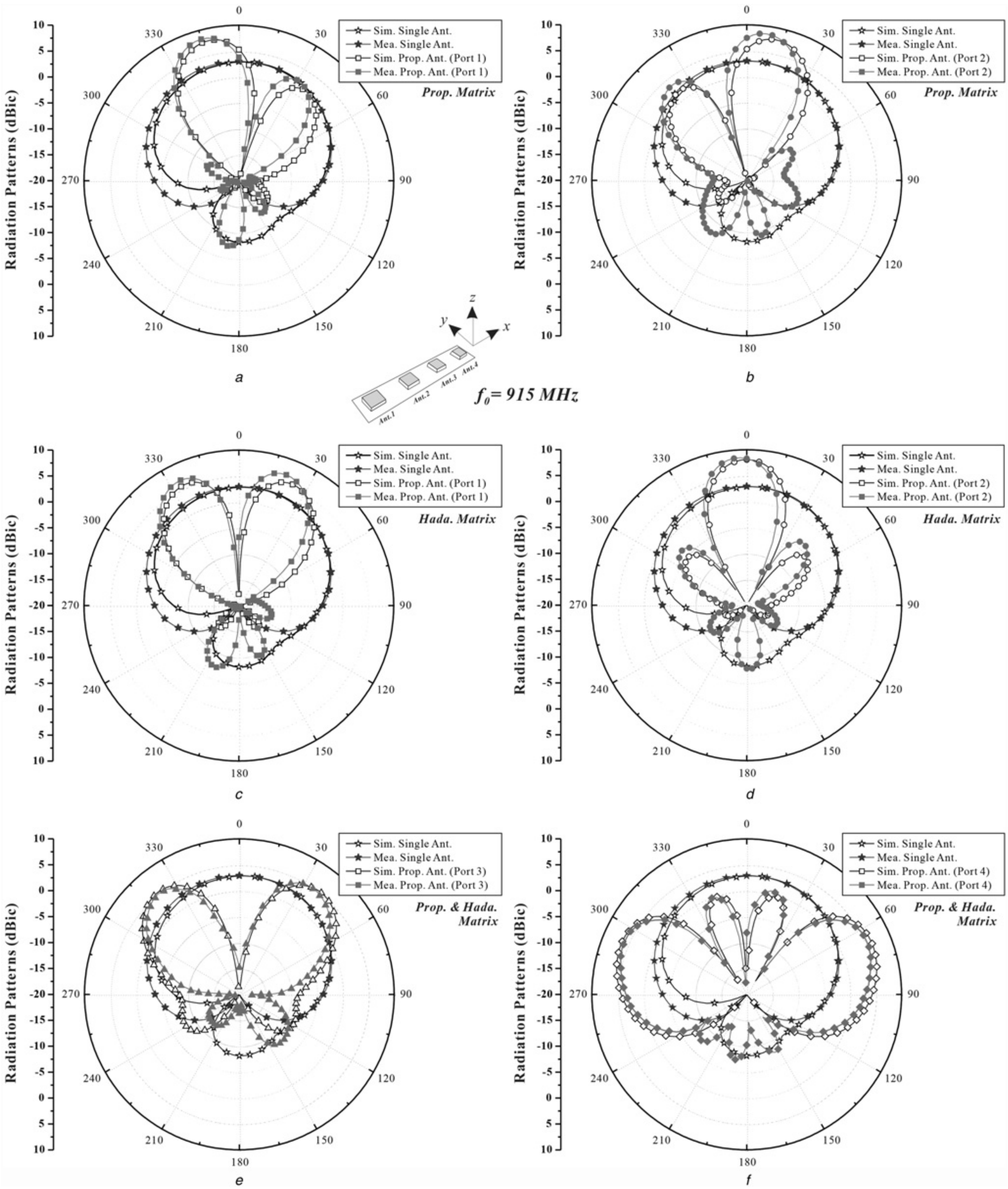

Fig. 8 *Simulated and measured radiation patterns of the antenna element and the proposed antenna array with regard to the input ports in xz-plane at the centre frequency (915 MHz)*

a Port 1 of the proposed matrix
b Port 2 of the proposed matrix
c Port 1 of the Hadamard matrix
d Port 2 of the Hadamard matrix
e Port 3 of the proposed or Hadamard matrix
f Port 4 of the proposed or Hadamard matrix.

0.15 m, respectively. For the CP characteristic, the tags are attached 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 Hadamard array antenna is divided into seven sectors from (A) to (F), which covers 180° of the front in Fig. 10.

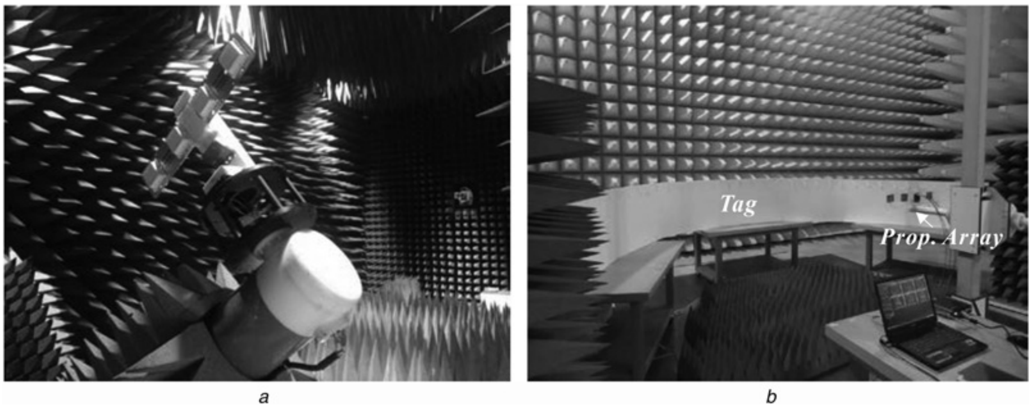

Fig. 9 *Measured setups*

a Gain and radiation patterns for the antenna array
b Tag identifications

The total number of the installed tags is 35, and the tags are encoded with an individual identification 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 designed proposed or Hadamard 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 is shown in Table 3 when the signal of 27 dBm at the operating frequency is fed by each port. Owing to the influence of the antenna coupling, tag identification depends on the position of the antenna element. However, in case of the 1 × 4 proposed or Hadamard matrix, tag identification can be achieved with dual interrogation zones without the interference between antenna elements in Table 3.

Furthermore, Table 3 shows the comparison results with the measured tag identification of the 1 × 4 square QSA array with regard to the all port switching with the direct feed and the designed proposed or Hadamard matrix. Since the tag identification in the square QSA array with the direct feed is overlapping between the ports, the total number of the recognised tags is 27, and the recognition rate of ∼77% has been obtained. On the other hand, the proposed antenna array has been 100% of the recognition rate in the widespread 35 tags.

4 Conclusion

In this paper, a beam-controlled antenna array incorporated with the quadruple feeding networks such as the proposed or Hadamard matrix has been proposed and demonstrated. The 4 × 4 proposed or Hadamard matrix generates multiple beams with three dual-beams or a single-beam and three dual-beams which can cover the wide spatial coverage of 180°. The main beam directions

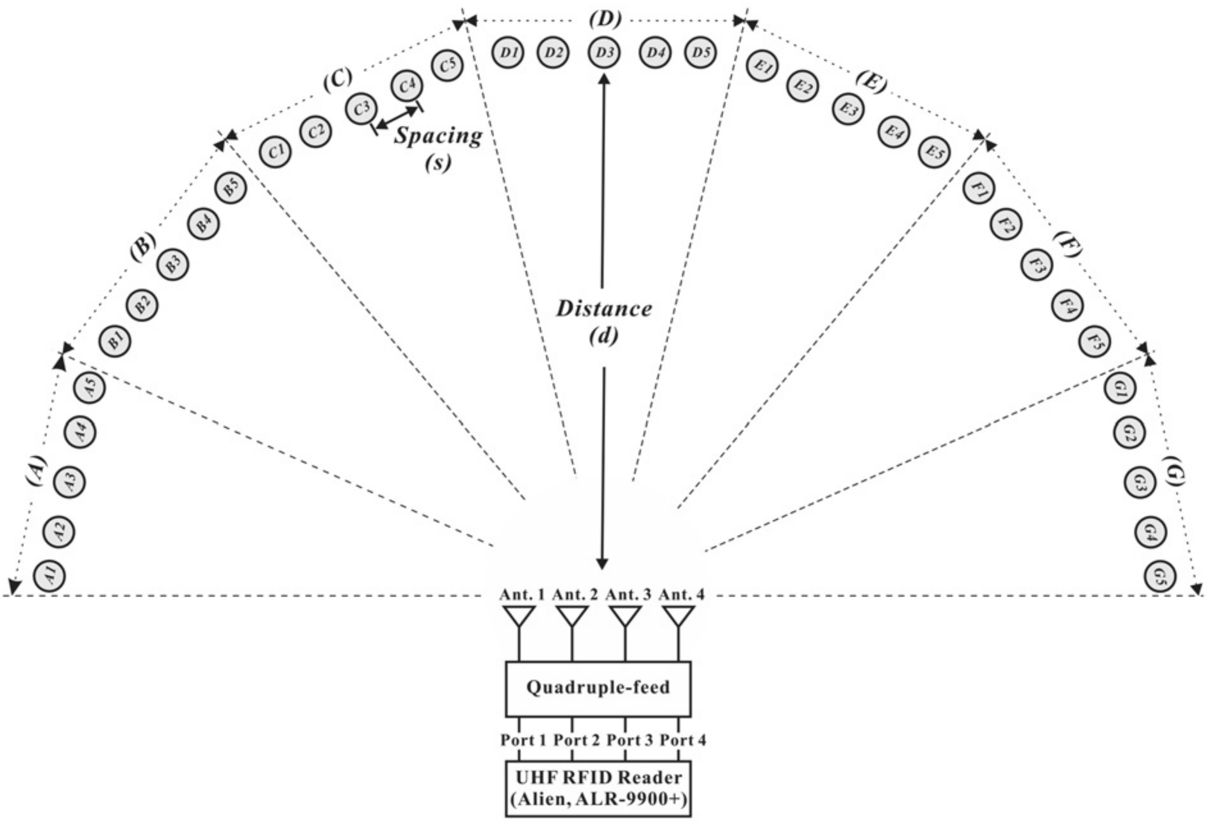

Fig. 10 *Tag identification setup for the verification of a wide coverage using a commercial UHF RFID reader with the quadruple beamforming networks*

Table 3 Comparison with the measured tag identification of a 1 × 4 antenna array with regard to the different feeds

Input port		'A' zone	'B' zone	'C' zone	'D' zone	'E' zone	'F' zone	'G' zone
direct feed	1	4, 5	1, 2, 3	–	3	2, 3	–	1, 2, 3, 4, 5
	2	–	–	4, 5	1, 2, 3, 4	1, 2	–	3, 4, 5
	3	–	–	2, 4, 5	3	2, 4, 5	1, 2, 3	-
	4	–	–	–	–	1, 2, 3, 5	1, 2, 3, 4, 5	1, 2, 3
switching	1–4	4, 5	1, 2, 3	2, 4, 5	1, 2, 3, 4	1, 2, 3, 4, 5	1, 2, 3, 4, 5	1, 2, 3, 4, 5
propopsed matrix	1	–	–	1, 2, 3, 4, 5	1, 2, 3	-–	–	–
	2	–	–	–	2, 3, 4, 5	1, 2, 3, 4	–	–
	3	–	2, 3, 4, 5	–	–	3, 4, 5	1, 2, 3, 4, 5	–
	4	1, 2, 3, 4, 5	1	–	–	–	4, 5	1, 2, 3, 4, 5
switching	1–4				all tags are identified			
Hadamard matrix	1			1, 2, 3, 4, 5		2, 3, 4, 5	1, 2	
	2			4, 5	1, 2, 3, 4, 5	1, 2		
	3	–	2, 3, 4, 5	–	–	3, 4, 5	1, 2, 3, 4, 5	–
	4	1, 2, 3, 4, 5	1	–	–	–	4, 5	1, 2, 3, 4, 5
switching	1–4				all tags are identified			

can be controlled by selecting the appropriate input port of the designed beamforming matrix. For the UHF RFID reader antenna array with the CP, the square QSA array with compact structure and excellent impedance matching has been applied. The fabricated antenna array operates at the 902–928 MHz band and produces three dual-beams at ±12°, ±39° and ±68° in the proposed matrix feeding network, a single-beam at 0° and three dual-beams at ±24°, ±39° and ±68° in the Hadamard matrix. By switching the multiple beams, the UHF RFID reader using the proposed antenna array can achieve the identifications of the RFID tag locations and dead-zone avoidance. Additionally, the proposed antenna array can be possible to control the beam directions according to the input port selection of the beamforming network.

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