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Enhancing Hajj pilgrimage experience and crowd management through Hajj-related keywords-based chipless RFID tags☆

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ABSTRACT

This study presents a novel application for deploying chipless RFID tags encoded with famous Hajj pilgrimage words. Inconspicuous, cost-effective, durable, and lightweight chipless RFID tags encoded with famous Hajj keywords of “Al-Ṣafa”, “Al-Marwa”, "Al-Tawaf, “Bidayat Al Sai”, and “Bidayat Al Tawaf” are designed and fabricated. Each keyword is etched using cooper material on the flexible Kapton substrate of 66 mm× 66 mm x 0.1 mm size. The resonance characteristics of each realized tag are analyzed by observing the frequency shift in their backscattered radar cross section (RCS) in the range of 1–10 GHz using CST software. The RCS of each tag provides a unique electromagnetic coding signature to it, owing to their different current distributions. Thus, provides easy, cheap, and durable deployments of such tags for handling and managing large crowds’ movements such as during Hajj. The fabricated tags RCS results have very good agreement with simulation results. The integration of proposed chipless RFID technology with Hajj-related keywords can improve pilgrimage experiences with enhanced crowd management using an integrated wayfinding system based on the Internet of Things (IoT) as well as the preservation of historical and cultural heritage.

1. Introduction

ONe of the most profound and treasured religious experiences for worldwide Muslims is a Hajj trip. Every year, millions of pilgrims gather in the holy city of Mecca, Saudi Arabia to take part in the spiritual journey [1,2]. The journey involves different scared steps of the congregation in Kabba during Tawaf, the stoning of pillars in Minna, stay, and prayers in Arafat.

The presence of such a sheer number of visitors often creates problems of overcrowding, bottlenecks, and confusion for the pilgrims at the key sites of Masjid Al Haram and Jamarat pillars [3]. This compromises the safety and well-being of pilgrims as well as creates detraction from the spiritual experience [3,4]. The physical barriers and fencing, route planning, signage, security personnel, surveillance and monitoring, communication systems with announcement and digital displays, travel plans, wristbands and identification cards, and pilgrim education are among the commonly employed traditional methods by the local authorities for sheer crowd handling [5–8]. These conventional techniques of crowd handling become insufficient and expensive when the complexities arise from the dynamic nature of a massive Hajj or similar large-scale crowd [9].

The advancement of technology has led to the development of various solutions for the efficient and effective management of large-size gatherings. Examples of such solutions are mobile applications, GPS-enabled location-based services (LBS), real-time visual monitoring of crowd density using drones and Internet of Things (IoT) sensors, artificial intelligence-enabled biometric systems, QR codes, big data analytics for the study of crowd pattern, and smart clothing [3,6,10–13]. Combinations of these technologies are being used for the handling of complex logistics of the Hajj pilgrimage. The role of various factors such

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as cost, infrastructure deployment, visitors' acceptance, education level of pilgrims, and cultural sensitivities affect the selection of a specific technology for such crowds [10,14,15].

Chipless radio frequency identification (RFID) tags have become a popular choice for different industries in the last decade [16–19]. They are designed using different kinds of metallic and dielectric resonating shapes only, without any additional components such as a battery or an antenna [20–25]. Also, the various designs of chipless RFID tags using Latin and Arabic alphabets are reported in [17,26–29]. The RFID reader excites the tag with an electromagnetic (EM) wave and records the backscattered EM response for the identification and detection of a specific tag. Researchers have proposed various time, frequency, and hybrid encoding techniques for such tags [26–28,30–33]. The electromagnetic signature of the chipless RFID tags depends on the type, shape, size, and structure of the tag [26–28,30–33].

Different techniques and strategies have been proposed in the literature for crowd management using RFID technology. The analysis of the received signal strength indicator (RSSI) from the RFID reader can be used for the detection of crowd speed, direction, crowd density, and flow rate through a particular zone [34]. The authors in [7,35] proposed the integration of various mobile technologies with RFID systems for the tracking of pilgrims and the provision of location-based services. Eladly *et al.* developed a real-time information density and density rate (RIDR) system for the prediction of zones that exceed the critical density in a mass gathering using RFIDs [36]. The studies of [37–39] demonstrated extensive crowd management through the development of integrated management models with chipped/chipless RFID tags as IoT nodes. The cost-effectiveness, low-cost scalability, and operational cost without the requirements of continuous maintenance make the chipless RFID tags an attractive option as compared to wearable sensors or mobile applications for crowd management [8,40].

This study proposed the integration of the chipless RFID tags in the sheer size crowd management solutions during large festivals such as Hajj. The study has developed some iconic and commonly used Hajj-words-based RFID tags that can be deployed at strategic locations for gathering real-time data about the pilgrim's movement. The deeply spiritual resonating words of "Al-Ṣafa - الصفا", "Al-Marwa-المروى", "Al-Tawaf- الطواف, "Bidayat Al-Sai- بداية السعى", and "Bidayat Al Tawaf- بداية الطواف" for Hajj pilgrims are engraved on the flexible Kapton substrate using copper material. The thickness of cooper material is 0.04 mm while the substrate has a thickness of 0.1 mm. The drawn words from CAD software are exported to EM software (CST MWS) and are etched on the 60 mm× 60 mm substrate. The observed backscattered RCS of each tag once illuminated with a plane wave in the frequency range of 1–10 GHz shows distinguish EM signature. The unique EM response of each tag provides ease in its real-time installation for sheer crowd management. Each tag is fabricated and has demonstrated good agreement with the simulated results. The advantages of realized novel Hajj-keywords RFID tags are multifolds (1) cheaper, durable, and sustainable design offers inexpensive deployment, (2) gathering of real-time crowd movement data for identification of congestion with the strategic installation of RFID readers at key locations; (3) providing location-specific information to the pilgrims for easy and smother navigation as well an enhanced spiritual experience without any distraction by integration the tags with digital wayfinding system.

The details of realized tags and their characterization are explained in the following sections.

2. Design of chipless Hajj-keywords tags

The hajj keywords "Al-Ṣafa - الصفا", "Al-Marwa-المروى", "Al-Tawaf- الطواف, "Bidayat Al-Sai- بداية السعى", and "Bidayat Al Tawaf- بداية الطواف" are chosen for their encoded chipless RFID tag designs owning to their common use and spiritual affiliation with the hajj pilgrims. The Arabic words are first written using 2D software like AutoCAD with a fixed font type and size. The 2D patterns are imported to the EM simulation software (CST Microwave Studio) to convert them to a three-dimensional shape. Each tag is then etched on a circular flexible Kapton substrate having a permittivity of 3.8 F/m and a loss tangent of 0.001. The circular substrate has a diameter of 60 mm and a thickness of 0.1 mm. The tag engraving is performed with a thickness of 0.04 mm and the cooper is assigned as the engraving material. Fig. 1 shows the 3D shape of the designed tags in the CST MWS.

The passive tags are excited with a dual-polarized plane wave in the frequency range of 1–10 GHz. The open boundary conditions were used for the EM characterization of the designed tags. The illumination of a plane wave introduces the current distribution around the resonating metallic tag shape. The pattern of this distribution depends on the shape and the electrical size of the tag. The electric field probes are placed in the far field to record the backscattered radar cross-section (RCS) waveforms in dual polarization (horizontal and vertical) for each tag as depicted in Fig. 2. The encoding of the realized tags is performed through the difference in the frequency-domain RCS properties of each tag for their distinct representation and identification.

3. EM characterization of realized tags

Fig. 3 shows the current distribution of the realized hajj word chipless RFID tags in the horizontal (HH) polarization. The term "HH" reflects that the plane wave is excited in horizontal polarization and the reader (probe) also records the horizontal backscattered RCS waveforms. Fig. 3(a) presents the current distribution of the Al-Safa keyword tag at the resonance frequency of 6.2 GHz. The illuminating plane wave changes the electric and magnetic fields around the metallic tag geometry. This brings variations in the induced currents and is reflected as the distributed current on the metallic tag geometry.

The change in current distribution for the other tags as compared to the Al-Safa tag can be noted in Fig. 3(b) –(e). For every tag, the current distribution is shown at one of its resonating frequencies. The shape pattern of the "Al-Marwa", "Al-Tawaf", "Bidayat Al-Sai", and "Bidayat Al Tawaf" tags are completely different from the Al-Safa tag. This ensures that characteristics of the current distribution for these tags are not only different from the Al-Safa tag but also vary from each other as can be observed from Fig. 3.

Similar observations can be made for the vertical polarization current distribution results of all simulated tags in Fig. 4. We can notice from Figs. 3 and 4 results that the role of the RFID reader incident wave polarization is also an important factor in the characterization of the EM properties of RFID tags. The current distribution for each tag is comprehensively different than the one for the cases in Fig. 3.

The co- and cross-polar backscattered reflections from the tags in response to the exciting plane waves are also examined in terms of the radar cross-section (RCS). Fig. 5 presents the simulated RCS results for the first tag *i.e.,* the Al-Safa tag. The black curves show the co-polar HH while the red curve corresponds to the co-polar VV RCS characteristics. Here the co-polar notion of 'HH' represents the horizontal plane wave illumination of the target tag and the horizontal reflected frequency encoded information recording by the RFID reader. The same is true for the case of VV case. In the case of cross-polar 'HV', the horizontal plane wave is zapped on the designed RFID tag, and the receiver is placed in the vertical polarization to record the backscattered EM signature of the tag. The results of the cross-polar VH were like the HV case for all analyzed word tags and hence are not reported here for brevity.

It can be observed from Fig. 5 that the co-polar HH RCS curve of the Al-Safa tag has prominent dips (representing resonance frequencies) at 6.2 GHz, 8.16 GHz, 8.63 GHz, and 9.06 GHz respectively. The peak values of the RCS amplitude are noticed at 3.9 GHz and 6.85 GHz for the same case. The resonance frequency characteristics change to 7.7 GHz and 8.2 GHz for the opposite co-polar configuration of VV. This is because of the different metallic structure excitation of the tag for the incident dual-polarized plane wave as was noticed in the current distributions of the same tag in Figs. 3(a) and 4(a) respectively. The EM

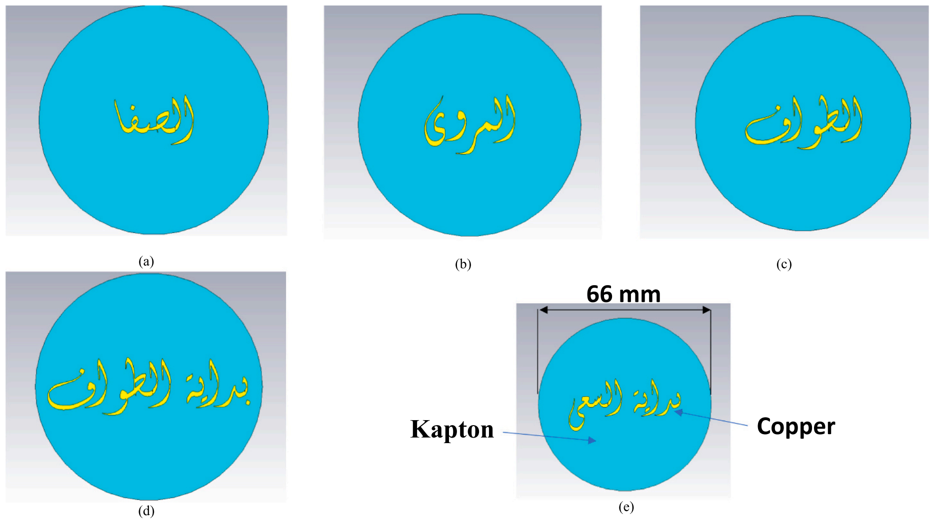

Fig. 1. Schematic of designed Hajj-keywords chipless RFID tags; (a) Al-Ṣafa – الصفا; (b) Al-Marwa-المروى; (c) Al-Tawaf- الطواف; (d) Bidayat Al Tawaf- بداية الطواف; (e) Bidayat Al-Sai- بداية السعى.

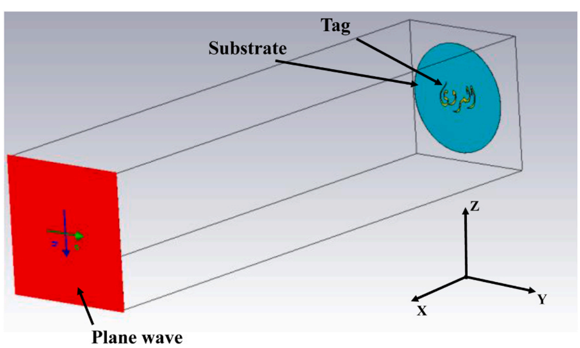

Fig. 2. EM simulation environment of realized tags.

signature of the Al-Safa tag shows different expected behavior for the cross-polar case of HV with only one key resonance at 6.17 GHz.

As was noticed in Figs. 3(b) and 4(b) the change in tag structure for the second keyword has brought prominent changes in the current distribution. This is also reflected in the RCS properties of the Al-Marwa tag as depicted in Fig. 6. The co and cross-polar RCS curves of this tag show different patterns when compared with the Al-Safa tag results in Fig. 5. The key resonance frequencies of this tag appear at 4.6 GHz and 6.18 GHz (HH), 5.68 GHz and 8.3 GHz (VV), and 4.45 GHz, 6.2 GHz, and 8.27 GHz (HV).

Similar observations about the variations in the RCS characterizations of Al-Tawaf, Bidayat Al Tawaf, and Bidayat Al Sai tags are made. Figs. 7–9 show the co- and cross-polar RCS waveforms for Al-Tawaf, Bidayat Al Tawaf, and Bidayat Al Sai tags respectively. Table 1 lists the significant resonance frequencies of all simulated tags.

As every designed tag exhibits a different geometric structure its resonance characteristic must be different because of different current

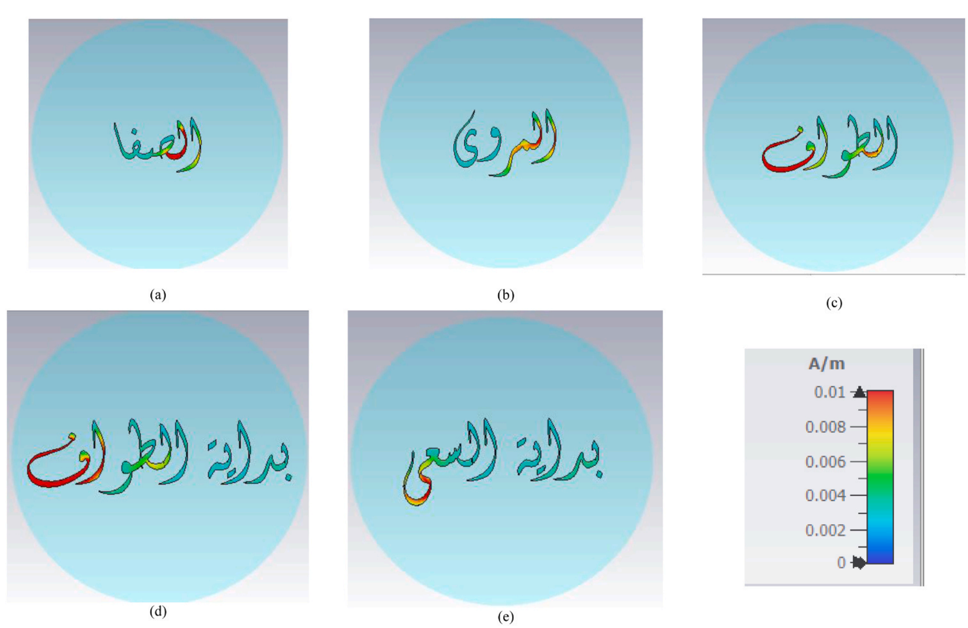

Fig. 3. Current distribution of simulated Hajj-keywords chipless RFID tags in horizontal polarization; (a) Al-Ṣafa – الصفا at $f = 6.2$ GHz; (b) Al-Marwa- المروى at $f = 6.18$ GH; (c) Al-Tawaf- الطواف at $f = 3.95$ GHz; (d) Bidayat Al Tawaf- بداية الطواف at $f = 3.9$ GHz; (e) Bidayat Al-Sai- بداية السعى at $f = 4.6$ GHz.

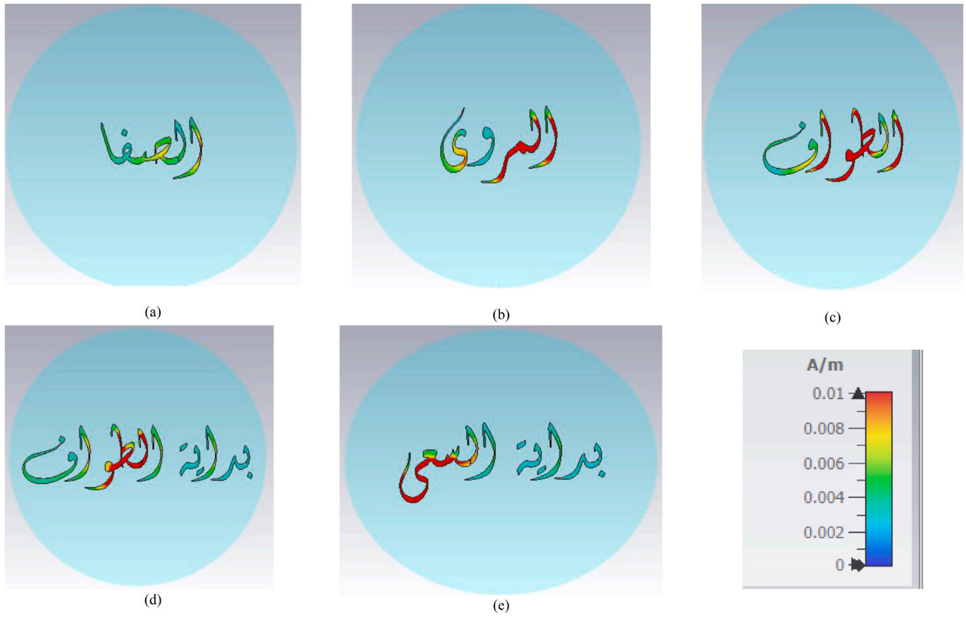

Fig. 4. Current distribution of simulated Hajj-keywords chipless RFID tags in vertical polarization; (a) Al-Ṣafa – الصفا at f = 8.2 GHz; (b) Al-Marwa- المروى at f = 5.68 GH; (c) Al-Tawaf- الطواف at f = 5.88 GHz; (d) Bidayat Al Tawaf- بداية الطواف at f = 4.87 GHz; (e Bidayat Al-Sai- بداية السعي at f = 3.75 GHz.

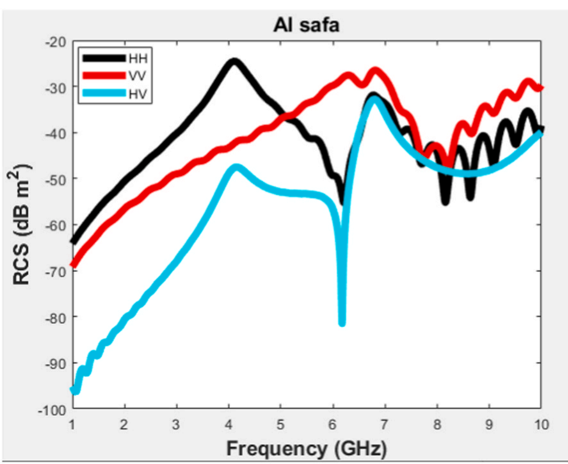

Fig. 5. Simulated RCS results of Al-Safa tag.

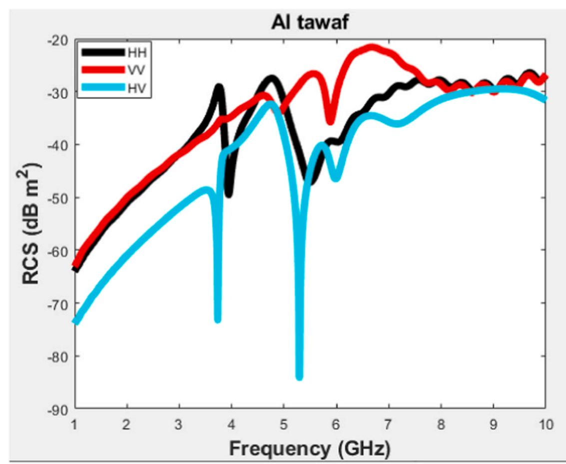

Fig. 7. Simulated RCS results of Al-Tawaf tag.

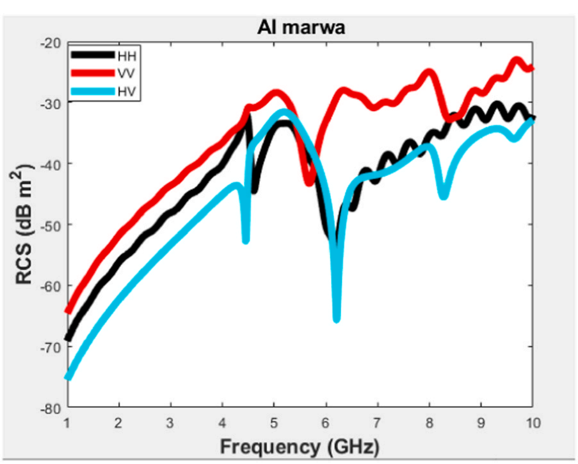

Fig. 6. Simulated RCS results of Al-Marwa tag.

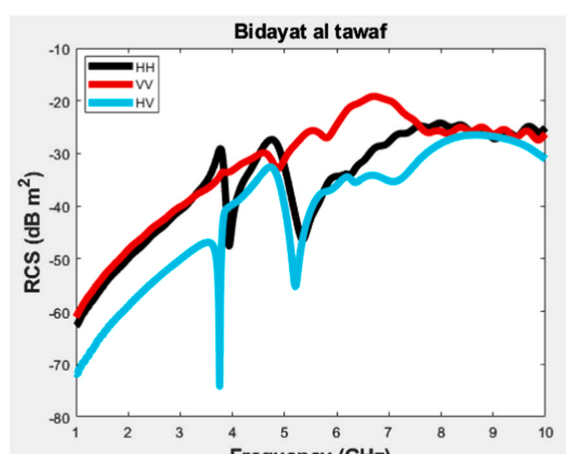

Fig. 8. Simulated RCS results of Bidayat Al Tawaf tag.

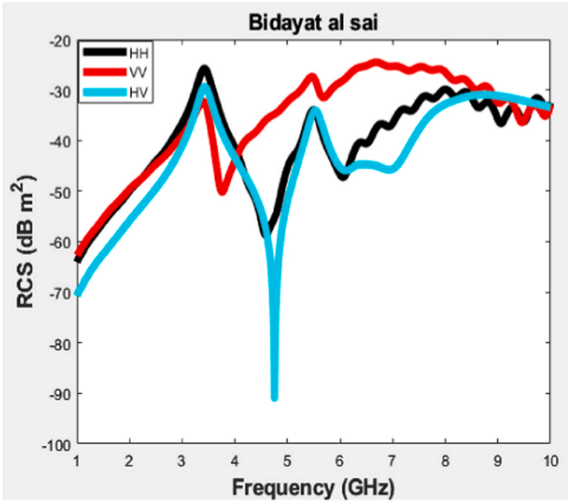

Fig. 9. Simulated RCS results of Bidayat Al Sai tag.

Table 1
Prominent resonance frequencies (in GHz) for the simulated tags.

	Polarization		
Tag	HH	VV	HV/VH
Al-Safa	6.2,8.16,8.63,9.06	7.7,8.2	6.17
Al-Marwa	4.6, 6.18	5.68,8.3	4.45,6.2,8.27
Al-Tawaf	3.95,5.49	4.9,5.88	3.73,5.29,5.98
Bidayat Al Tawaf	3.9,5.3	4.87	3.75,5.2
Bidayat Al Sai	4.6, 6.04	3.75,5.68	4.75

distributions as demonstrated in Figs. 3 and 4. The observed different resonance frequencies and waveform patterns in Figs. 5–9 and Table 1 prove that each analyzed tag has a unique EM signature. This eases the process of their detection and identification with the lesser impact of noise as the resonance nature of metallic tags is quite distinguishable in both co-and cross-polarizations.

4. Fabrications of Hajj-keywords tags

To evaluate the exactitude of the simulated results, the chipless Hajj Arabic RFID tags in question were fabricated on a flexible Kapton substrate using advanced photolithography techniques. Fig. 10 illustrates the resulting fabricated samples, each possessing a cross-sectional area measuring $66 \times 66 \times 0.1$ mm^3.

The real-time RCS characterization of the fabricated tag is performed in the anechoic chamber as illustrated in Fig. 11. A bistatic measurement configuration is used for the recording of RCS results of the tag under test. The measurement setup comprises two horn antennas, each with a gain of 12 dBi, as well as foam, wooden support, and fabricated tag.

Fig. 10. Fabricated Hajj keywords prototypes.

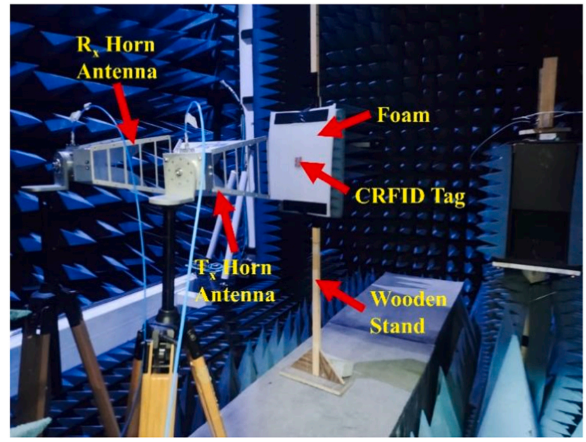

Fig. 11. Measurement setup for the characterization of fabricated tags.

During the measurements, the tag is affixed to the foam. Both the transmitting and receiving antennas are connected to a Vector Network Analyzer (VNA) E8362B model. The tag is positioned in front of the antennas, and the S-parameter S_{21} is recorded. For each tag, the measurements are carried out three times. The measurements are carried out separately for the co-polar case and cross-polar case. Initially, both the transmitting and receiving horn antennas are oriented in the horizontal (H) polarization to measure S_{21} HH. Then, the polarization of the antennas is changed to vertical (V), and S_{21} VV is measured. Finally, both the horn antennas are placed in inverse orientation to measure S_{21} HV. The effect of the used foam and environment is removed from the recorded S-parameters by measuring the environment response without the tags.

5. Comparison of measured and simulated results

The measurement process consists of several steps. Initially, the S_{21} parameter of the tag (S_{21}^{tag}) is measured. Subsequently, the tag is removed from the setup to account for static noise, and ($S_{21}^{isolation}$) is then measured. Lastly, to compensate for the impact of the horn antennas, the (S_{21}^{ref}) of a reference metallic sheet with a known RCS (σ^{ref}) is measured. The final RCS of the tag is determined using Eq. (1) from [41].

$$\sigma^{tag} = \left[\frac{S_{21}^{tag} - S_{21}^{isolation}}{S_{21}^{ref} - S_{21}^{isolation}}\right]^2 .\sigma^{ref} \tag{1}$$

The comparison between the measured and simulated results is

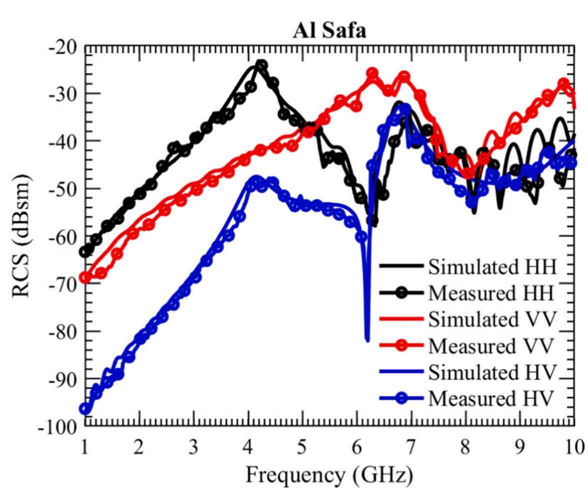

Fig. 12. Simulated and measured RCS results of Al-Safa tag.

presented in Figs. 12–16. The figures effectively differentiate between the RCS responses for the co-polar and cross-polar orientations. Moreover, the figures display both the highest and lowest RCS levels, making them easily discernible.

The comparison of co-polar and cross-polar results of the simulated and measured waveforms of the Al-Safa tag is illustrated in Fig. 12. A very good agreement between the full-wave and measurement waveforms can be noticed in Fig. 12. Figs. 13–16 present the comparison of simulated and measured RCS curves for the Al-Marwa tag, Al-Tawaf, Bidayat Al-Tawaf tag, and Bidayat Al-Sai tag. A strong correlation between the measured and simulated results can be observed in Figs. 13–16 for all realized tags. The observed prominent response frequencies of the prototype tags are exactly as shown in Table 1 for the simulated tags.

The real-time deployment of proposed chipless RFID tags in different densely crowded sites such as Hajj, Kumbh Mela, and Vatican services would require the installation of RFID readers at strategic locations for consistent tag readability and minimization of any potential interference. The optimal strategic installment of readers at entrances, exits, and critical crowd movement paths would ensure reliable coverage of high-traffic points with minimal maintenance requirements [9,42]. Specific word tags for dedicated cultural or event-specific requirements of mass gatherings of Kumbh Mela, and Vatican services could be easily designed. As each designed tag has a unique electromagnetic signature, the role of the tag-to-tag interference will be minimal. For enhanced decoding accuracy of individual tags, advanced signal processing techniques including machine learning algorithms, filtration, and separation algorithms could be employed [9,42].

The integration of artificial intelligence (AI) could enhance the proposed framework performance with optimized resource allocations with additional insights into predictive crowd analytics for the identification of congestion points and crowd movements [9,42]. However, sufficient computational resources to handle and analyze large-scale real-time data being received from multiple tags and readers will be required. For faster processing, distributed computing approaches such as edge computing at readers node along with cloud interfaces could be deployed [42]. For a user-friendly interface and uninterrupted experience for pilgrims of diverse backgrounds, simple multilingual audio or visual navigation cues can be added to the system. Additional features of emergency response or lost pilgrim assistance in the framework can enhance the value of the implemented system. Overall, the cheap mass production, passive operation without any power requirement for tags, and optimal infrastructure requirements make such a chipless RFID tags-based solution a better and sustainable choice for large-scale crowd management.

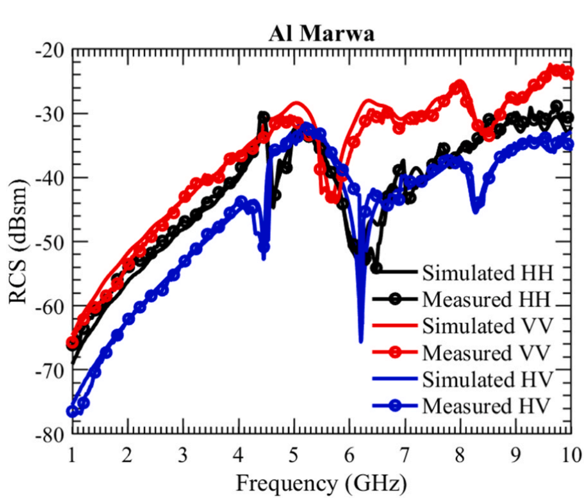

Fig. 13. Simulated and measured RCS results of the Al-Marwa tag.

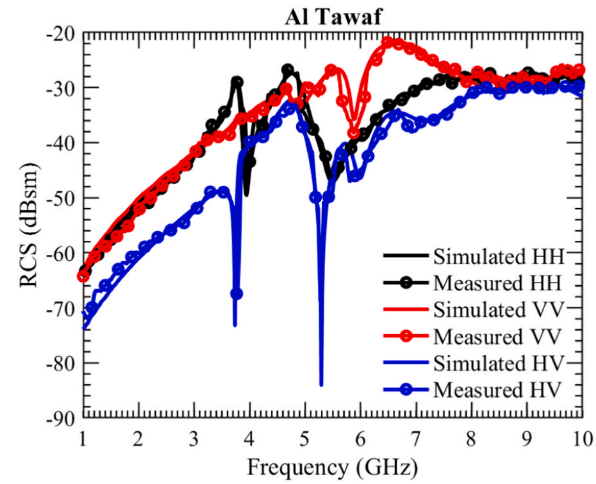

Fig. 14. Simulated and measured RCS results of Al-Tawaf tag.

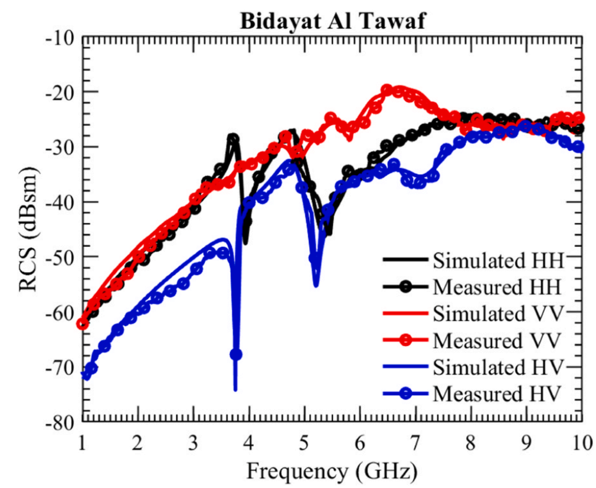

Fig. 15. Simulated and measured RCS results of the Bidayat Al-Tawaf tag.

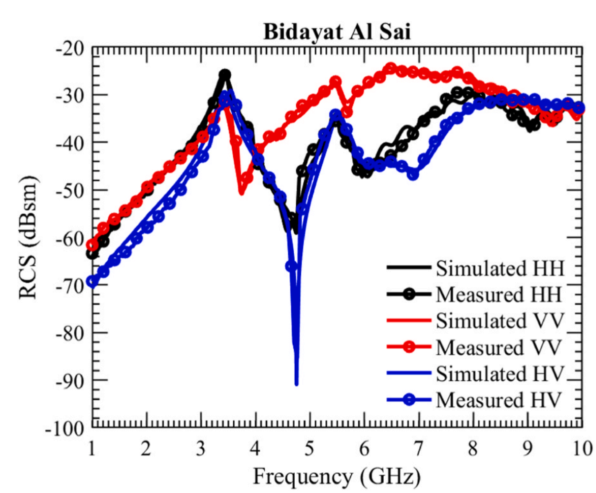

Fig. 16. Simulated and measured RCS results of the Bidayat Al-Sai tag.

6. Conclusion

This study has presented the design and analysis of novel chipless RFID tags embedded with five different Hajj-related keywords. The “Al-

Ṣafa", "Al-Marwa", "Al-Tawaf, "Bidayat Al Sai", and "Bidayat Al Tawaf" tags are designed and fabricated using a flexible Kapton substrate with a cross-sectional area of 66 mm× 66 mm and thickness of 0.1 mm. The simulated and measured RCS results of realized durable and lightweight tags show very good agreement. The RCS analysis of the realized tags in both co- and cross-polar configurations provides additional advantages of enhanced coding density and spectral efficiency. The realized tags can be used for the potential applications of crowd management and navigation of sheer crowds during Hajj or such relevant gatherings. The integration of proposed tags with a wayfinding system can provide real-time insight into crowd movement to the authorities for efficient management of religious practices as well as the preservation of historical sights.

CRediT authorship contribution statement

Hatem Rmili: Project administration, Methodology, Funding acquisition, Conceptualization. **Mohammed Bensaleh:** Conceptualization. **Farooq Tahir:** Writing – original draft, Validation, Investigation, Conceptualization. **Mohammed Aseeri:** Validation, Methodology, Investigation. **Muhammad Noman:** Software, Methodology, Data curation. **Bandar Hakim:** Supervision, Resources, Funding acquisition, Conceptualization. **Jawad Yousaf:** Writing – original draft, Methodology, Formal analysis. **Oussama Boularess:** Validation, Software, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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