IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received July 12, 2019, accepted August 30, 2019, date of publication October 7, 2019, date of current version October 17, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2945789

A Fuzzy-Based Angle-of-Arrival Estimation System (AES) Using Radiation Pattern Reconfigurable (RPR) Antenna and Modified Gaussian Membership Function

MOHD ILMAN JAIS[1], (Student Member, IEEE), THENNARASAN SABAPATHY[1], (Member, IEEE), MUZAMMIL JUSOH[1], (Member, IEEE), R. BADLISHAH AHMAD[1], (Member, IEEE), MOHD HAIZAL JAMALUDDIN[2], (Member, IEEE), MUHAMMAD RAMLEE KAMARUDIN[3], (Senior Member, IEEE), PHAKLEN EHKAN[1], (Member, IEEE), L. MURUKESAN LOGANATHAN[1], (Student Member, IEEE), AND PING JACK SOH[4], (Senior Member, IEEE)

[1]Bioelectromagnetics Research Group, School of Computer and Communication Engineering, Universiti Malaysia Perlis, Arau 02600, Malaysia
[2]Wireless Communication Centre, School of Electrical Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Malaysia
[3]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, Parit Raja 86400, Malaysia
[4]CoE Advanced Communication Engineering, School of Computer and Communication Engineering, Universiti Malaysia Perlis, Arau 02600, Malaysia

Corresponding authors: Thennarasan Sabapathy (thennarasan@unimap.edu.my) and Muzammil Jusoh (muzammil@unimap.edu.my)

ABSTRACT Angle-of-arrival (AOA) estimation is an important factor in various wireless sensing applications, especially localization systems. This paper proposes a new type of AOA estimation sensor node, known as AOA-estimation system (AES) where the received signal strength indication (RSSI) from multiple radiation pattern reconfigurable (RPR) antennas are used to calculate the AOA. In the proposed framework, three sets of RPR antennas have been used to provide a coverage of 15 regions of radiation patterns at different angles. The salient feature of this RPR-based AOA estimation is the use of Fuzzy Inferences System (FIS) to further enhance the number of estimation points. The introduction of a modified FIS membership function (MF) based on Gaussian function resulted in an improved 85% FIS aggregation percentage between the fuzzy input and output. This later resulted in a low AOA error (of less than 5%) and root-mean- square error (of less than 8°).

INDEX TERMS Angle-of-arrival (AOA), fuzzy inferences system (FIS), radiation pattern reconfigurable (RPR) antenna, membership function (MF).

I. INTRODUCTION

Angle of Arrival (AOA) estimation for direction finding has been actively investigated throughout the past few decades. Historically, the direction-finding technique is found in electronic surveillance applications. In recent days, direction finding is fundamental to wireless sensor networks (WSN), which in turn can be integrated into applications such as patient monitoring systems and localization systems.

The motivation of this work is the deployment of received signal strength indication (RSSI) information as mechanism to the AOA estimation system. AOA is defined as the angle between transmitter and receiver with reference direction, known as orientation. AOA estimation system (AES), which has become an essential demand in WSNs, can be performed by either phased arrays [1], or steerable antenna aid by mechanical elements [2] or assisted by multi-antennas [3], [4]. The phase antenna arrays usually tracks the angle by the amplitude and phase of the incoming signals [5]–[8]. These information are further processed for AOA estimation using a complex digital signal processor and signal processing algorithms such as least mean square (LMS), Recursive Least Square (RLS) and MUltiple Signal Classification (MUSIC) [9]–[11]. However, in less complex systems proposed recently [4], [12]–[15] in only the RSSI is needed to successfully estimate AOA. In other words,

The associate editor coordinating the review of this manuscript and approving it for publication was Jenny Mahoney.

the reduced processing of complex signal information eventually reduces the overall computational complexity of the AOA estimation system.

Besides this, various approaches to realize AOA estimation system. The AOA estimation systems may use multiple static or array antennas known as smart antennas with signal processing units for AOA estimation. The most common method is using antenna arrays to measure the signals time of-arrival (ToA) differences at different receivers [16], [17]. Authors in [18] have proposed the use of two antennas to estimate the AOA at a receiver node using measured RSSI. Another method uses antenna arrays and RSSI measurements on each antenna, where the AOA can be estimated using the RSSI ratio [19]–[21]. An AOA systems can also utilize radiation pattern-reconfigurable (RPR) antennas [22]–[25]. The use of these RPRs on stationary systems enables radiation pattern reconfiguration without any physical impact towards the antennas. This can be performed by controlling each antenna on or off states using algorithms [24]. In this paper, the AOA estimation uses RPR antennas controlled by RF Pin diode as switches. The main advantage of RPR antenna approach is the reduced number of antennas and the improved coverage angles. The authors in [12] proposed a system of 12 static antennas to cover the full 360° direction, whereas this work uses only three RPR antennas for the same coverage. Moreover, the ability of the AOA estimation method using the RPR antennas in this work are enhanced using an embedded Fuzzy Inferences System (FIS) [26]–[29]. The main contributions from the proposed technique are: (i) improved AOA estimations using minimal number of antennas with less complexity and (ii) improved accuracy of the AOA estimation with FIS framework which uses modified Gaussian membership function (MF).

The rest of the paper is organized as follows: Section II explains the theoretical background of the fuzzy approach, followed by the detailed hardware configuration in Section III. The conventional estimation algorithm and associated experimental data are presented in Sections IV and V, while the improved algorithm and experimental results are presented in Section VI. Finally, conclusion remarks for this work are provided in Section VII.

II. THEORETICAL BACKGROUND OF FUZZY APPROACH

An adaptive switching algorithm is required in the proposed AES to properly select the beam forming direction of the RPR antenna when an incoming RSSI is effectively traced. To facilitate such adaptive switching, a fuzzy inference system is introduced which uses the radiation pattern switch condition (either left or right) as the input variables.

A conventional crisp logic set represent the degree of membership of any object in the set is either 0 or 1. This is similar to digital logic circuit, which differentiates elements into two extreme categories, such as good or bad, yes or no and black or white. For instance, consider the RSSI indicator which consists of two scenarios, −50 dBm and below can be considered as weak signal strength and beyond −50 dBm as strong signal strength. If the RSSI level is expressed as a binary-valued crisp set, 0 is the crisp value for any RSSI level below −50 dBm, and 1 is the crisp value for RSSI level above −50 dBm. This will lead to increase angle estimation error. The fuzzy membership function (MF) set further refines the concept of crisp set by extending binary value sets to multi value sets. The degree of membership (known as membership value) in a fuzzy set X is characterized by real value either 0 or 1. In general, the fuzzy set X in a universe of discourse U (X: U [1, 0]), can be defined as follows:

$$X = \{u, \mu_x(u) | u \in U \quad (1)$$

where $\mu_x(u)$ is the membership function (MF) of u in X. The fuzzification is the process mapping the real input to MF form input. The MF is associated with the fuzzy set and maps a real input value to an appropriate membership value. The triangular membership function and the trapezoidal membership function [30] are two types of membership functions which commonly used in most of applications with the advantage of simplicity [31]. Figure 1 shows the triangular membership function, which is defined by:

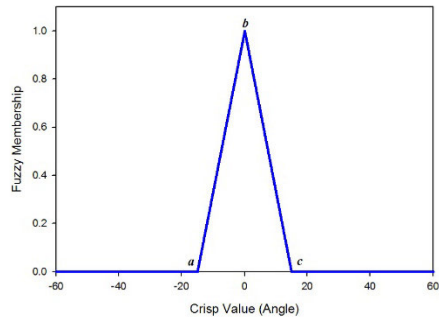

FIGURE 1. Triangular membership function.

$$\mu_y(x) = \begin{Bmatrix} \text{(x-b)} + 1, & a \le x \le b \\ \text{(b-x)} + 1, & b \le x \le c \\ 0, & elsewhere \end{Bmatrix} \quad (2)$$

The trapezoidal membership function depicted in Figure 2 is given by [30]:

$$\mu_y(x) = \begin{Bmatrix} \frac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \frac{d-x}{d-c}, & c \le x \le d \\ 0, & elsewhere \end{Bmatrix} \quad (3)$$

Both the triangular-MF and the trapezoidal-MF are deemed unsuitable for this proposed system. This is due to the aim of this work, which is to map the radiation pattern as the fuzzy input (membership function), whereas their fuzzy abilities will be utilized in the decision-making process.

The Gaussian-MF is deployed to achieve this objective. The Gaussian-MF can be defined by:

$$\mu_x(u) = exp^{\frac{-(\text{X-C})^2}{2\sigma^2}} \quad (4)$$

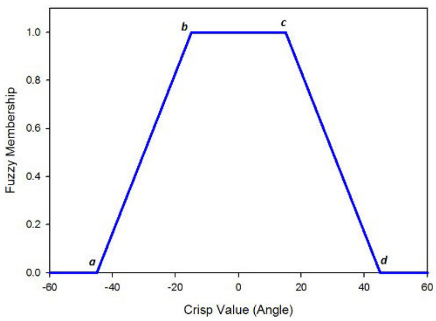

FIGURE 2. Trapezoidal membership function.

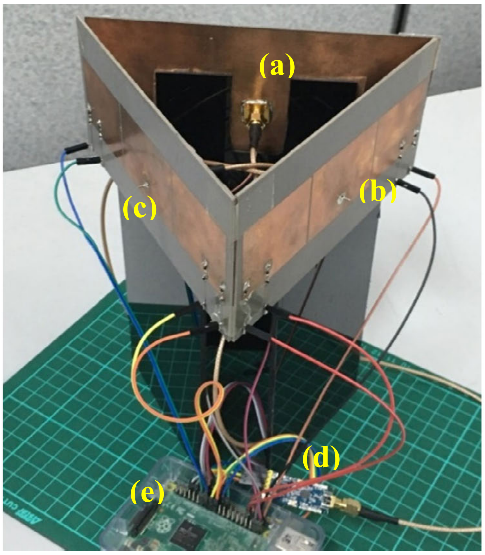

FIGURE 3. The AOA estimation system. (a) RPR A, (b) RPR B, (c) RPR C, (d) WiFi module, and (e) Raspberry-Pi.

where x represents crisp value, c is the center of the Gaussian-MF and σ represents the width of Gaussian-MF. In this work, the direction angle is the crisp value. The modified MF based on Gaussian curves named as a Pattern Membership Function (Pattern- MF) will be presented in this paper, in Section V. The FIS related work has been performed using SciKit library toolbox with Python version 2.7. The comparison and analysis of FIS aggregation are performed with various types of membership function as discussed earlier.

III. HARDWARE, SOFTWARE AND EXPERIMENT SET-UP

This section discusses the hardware and software implementation involved in this proposed AES. The proposed AOA Estimation System (AES) prototype is developed using three major components: A Single Board Computer (SBC), Wi-Fi Module, and Radiation Pattern Reconfigurable (RPR) antennas as depicted in Figure 3. Figure 4 depicts the schematic layout of the system. It shows that each RPR antenna is connected with a Wi-Fi module (SZ05). This module is the main gateway for the collection of RSSI and AOA estimation purposes. This module bridges the Raspberry-Pi and three RPR antennas to complete the AES, as illustrated in Figure 3. An UART controller circuit is required to allow three sets of Wi-Fi modules share a same GPIO pin the Raspberry-Pi.

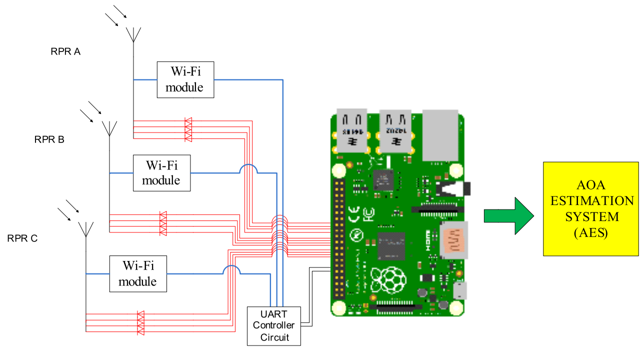

FIGURE 4. System layout of the proposed AES.

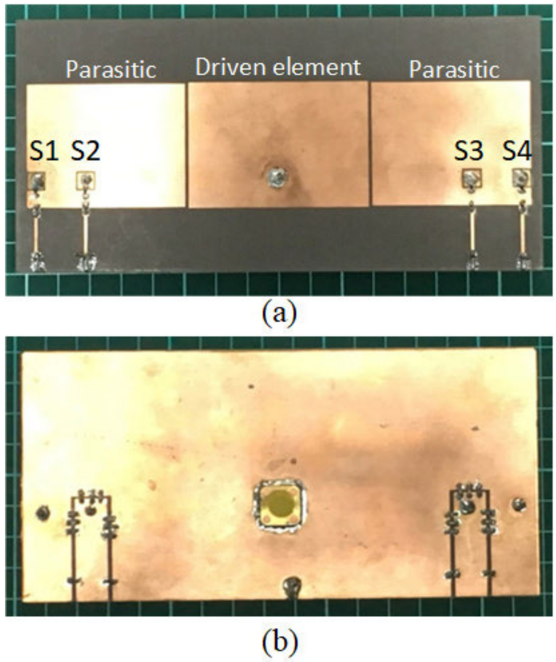

FIGURE 5. RPR Antenna (a) Front and (b) Back.

Figure 5 shows the structure of the RPR antenna developed for the use of the AES system. The antenna consists of a driven element and two parasitic elements that can enable beam steering with the use of RF switches (BAR50-02V PIN Diodes). The related dimension of the antenna is illustrated in Figure 6. The antenna is fabricated using Taconic substrate with a relative permittivity of 2.2, a substrate height of 1.6 and loss tangent of 0.0009. Four RF switches are used to control the radiation pattern reconfiguration for each RPR. The connections of the RF switches from the RPR antennas to the Raspberry-Pi is shown in Figure 4, whereas the respective switching connections to the GPIO of the Raspberry-Pi are tabulated in Table 1. On the other hand, the switching conditions and related beam characteristics are tabulated in Table 2. Each antenna has an average gain of 7.5 dBi and an average efficiency of 80 %.

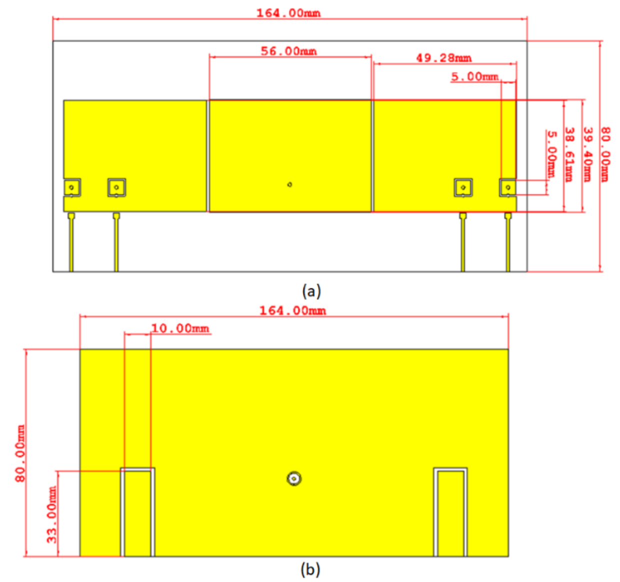

FIGURE 6. Layout of the RPR (a) Front and (b) Back.

TABLE 1. RF Switches connections with related GPIO header for each RPR antenna.

RF- SWITCH	RPR A GPIO HEADER	RPR B GPIO HEADER	RPR C GPIO HEADER
I	GPIO 32	GPIO 31	GPIO 7
II	GPIO 36	GPIO 33	GPIO 11
III	GPIO 38	GPIO 35	GPIO 13
IV	GPIO 40	GPIO 37	GPIO 15
GND	GPIO 30	GPIO 39	GPIO 9

TABLE 2. Beam pattern characteristics of RPR antenna.

	Switch Mode				Direction of the main Beam (θ)
Mode	S1	S2	S3	S4	
I	ON	ON	ON	ON	0°
II	ON	ON	OFF	OFF	-30°
III	OFF	OFF	ON	ON	+30°

The single board computer (SBC) used in this work is a Raspberry-Pi to detect and process the incoming RSSI values and as a switch controller for the RPR antennas. In this research, the source codes are tested on Raspberry-Pi developed using Python version 2.7. The Python code in this work is used to capture and process the incoming RSSI, and to control RF switches of RPR antennas. This code is also used to develop FIS assisted by SciKit library, that used to perform the decision-making process of AOA estimation with enhanced and improved the number of estimation points.

Figure 7 illustrates the radiation pattern of the three RPR antennas shown in Figure 5, covering an angle of about 360°. Each antenna is capable of reconfiguring its beam to the three main directions, at −30°, 0°, and +30°. This enables the three antennas to provide nine regions of AOA estimation.

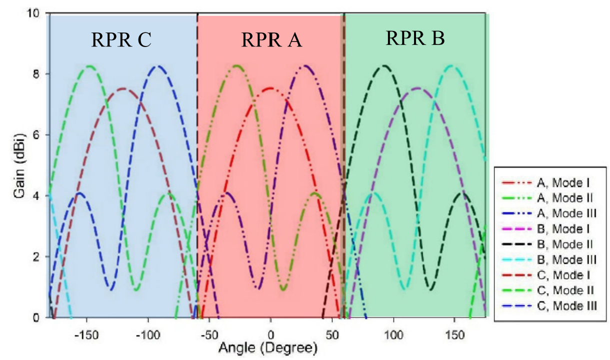

FIGURE 7. The radiation patterns of the three RPR antennas with all mode configurations.

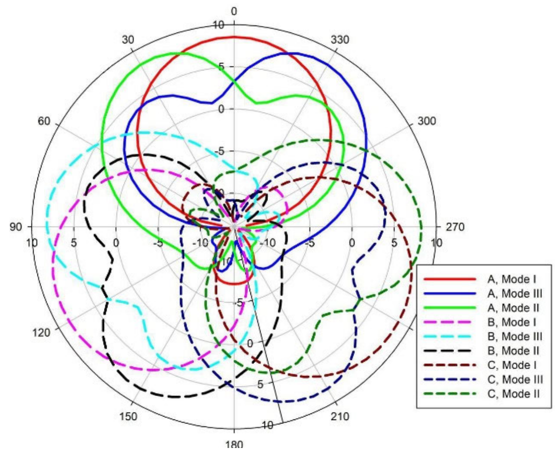

FIGURE 8. The polar plot of the proposed AES.

The polar plot of the radiation pattern of the AES for 360° AOA estimation coverage is shown in Figure 8.

IV. PRELIMINARY EXPERIMENTAL AOA ESTIMATION

The measurement of proposed AES illustrated is conducted in a free space environment. It functions as a receiver (Rx) to measure reference RSSI (RSSI r, θ) from different directions and at distances of 1 m, 5 m and 10 m from a 2.4 GHz transmitter. To establish a good line-of-sight (LOS) between the proposed AES and transmitter (Tx), both sides are properly aligned to be at the same heights, with the absence of physical obstacles. Incoming RSSI values are obtained at every 10° and the measurement is repeated 10 times.

Figure 9 shows the maximum incoming RSSI values from all three RPR antennas based on each activated mode. This preliminary experimental results allow the setup of RSSI(r, θ) as the reference to further calculate the AOA estimation error.

The flow to collect the incoming RSSI values from the receiver for AOA estimation purpose is described as follows: (i) Tx is first aligned to have line-of-sight (LOS) with the AES; (ii) the AES scans for maximum RSSI values in each region; (iii) comparison between the incoming RSSI is performed by Python within the Raspberry-Pi

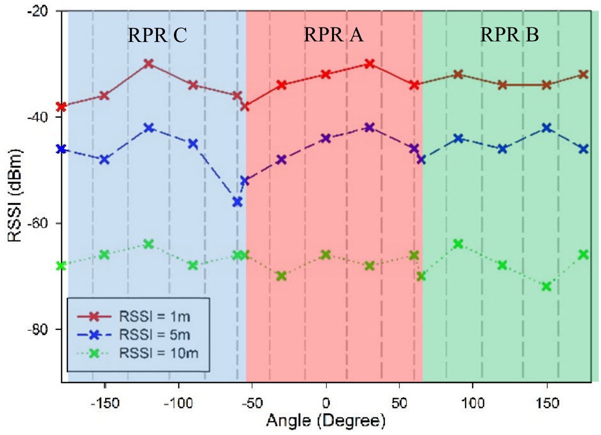

FIGURE 9. References AOA estimation for different TX and Rx gap.

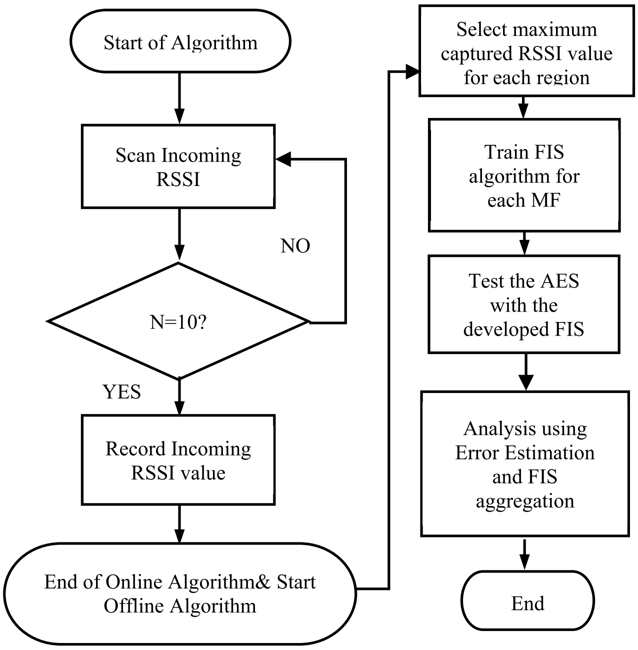

FIGURE 10. Flowchart of the development and implementation of AOA estimation system (AES).

SBC; (iv) the SBC then activates the Pin-Diode on RPR antennas for AOA estimation based on the highest received RSSI value.

Figure 10 summarizes the overall proposed AES process and implementation. It demonstrates that the overall code or command flow to execute the proposed system, starting form scanning the incoming RRSI until the proposed system decides on the direction where the strongest RSSI is coming from. This code first scans the incoming RSSI for all configuration for each RPR antennas. The RSSI value recorded and use as references value to estimated location of Tx (based on higher RSSI). Figure 8 shows the measured AOA (RSSIm, θ) values compared to the reference AOA estimation (RSSIr, θ) with a 5 m distance between Tx and Rx. It is validated that each RPR antenna generated three different regional coverage areas, depending on the Pin diode configuration, denoted in this work as mode. Table 3 summarizes these modes and the regions covered by each RPR antenna in different modes.

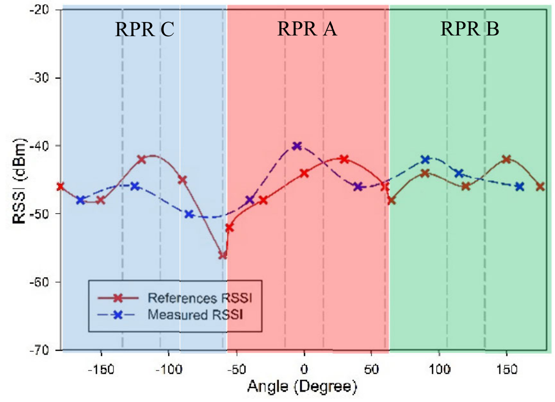

FIGURE 11. Measured AOA estimation (RSSIm, θ) vs reference AOA estimation (RSSIr, θ).

TABLE 3. Region of RPR antennas without FIS.

RPR Antenna	Region	Mode	Angle Covered
A	i	II	-60° to -15°
	ii	I	-14° to 15°
	iii	III	16° to 60°
B	i	II	61° to 105°
	ii	I	106° to 135°
	iii	III	136° to 179°
C	i	II	-61° to -105°
	ii	I	-106° to -135°
	iii	III	-136° to -179°

Both measured AOA estimation (RSSIm, θ) and reference AOA estimation (RSSIr, θ) agreed to each other as shown in Figure 11. The mode I of RPR antenna covered small region show almost the location of maximum RSSI value for both measured and reference AOA estimation.

On other hand, wide regions covered by mode II and III shown the maximum RSSI value point for RSSI m, θ is slightly differ from RSSI r, θ.

Thus, the AOA estimation error for mode I less than mode II and III of RPR antenna. This scenario has happened to each RPR antenna. The AOA estimation error occurs especially the maximum incoming RSSI comes from region mode II and III.

V. EXPERIMENTAL ESTIMATION ADOPTING FUZZY INFERENCES SYSTEM (FIS)

The simple algorithm for AOA estimation from the previous section is conducted by continuously switching the beams of the RPR antenna to detect maximum RSSI. Once this is determined, the AOA can be estimated according to the maximum-detecting beam. For instance, a maximum RSSI obtained at RPR A when operated in mode I indicate the AOA region from $-150°$ to $150°$. However, the exact region could not be streamlines with limited number of estimation points. Therefore, an adaptive switching algorithm is required in the AOA estimation system to properly select the direction of reconfigurable antenna beam pattern when incoming RSSI is traced. To enable such adaptive switching, a fuzzy logic

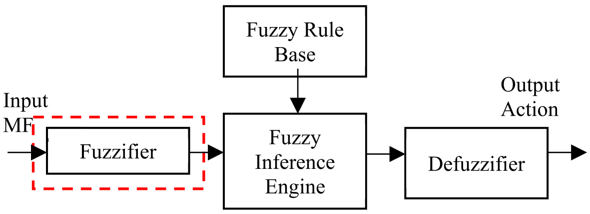

FIGURE 12. Basic structure of fuzzy inferences system (FIS).

controller, which uses the radiation pattern and scanning switch condition (either left or right) as the input variables, is proposed. Using the FIS system, additional AOA estimation regions are added by subdividing each RPR radiation patterns into five regions for a total of 15 regions.

The general structure of FIS consists of three basic parts: the fuzzification process (fuzzifier) at the input terminal, the FIS core consist the inference engine which is built on the fuzzy logic control rule base, and the defuzzification process (defuzzifier) at the output terminal, as shown in Figure 12 [32]. The fuzzy engine contains a set of fuzzy rules. These rules control the operation of the whole fuzzy inferences system (FIS). These fuzzy operators execute the (AND), (OR) and (NOT) operations which are used to formulate the IF-THEN rules. The IF-THEN rules test any considerations from the input in the fuzzy engine before responding at defuzzifier as its output. The concept of the IF-THEN rules is almost similar with if-else rules in programming, but involves a larger scale of considerations and is capable to operate in multiple-value sets.

The fuzzifier locates the membership function (MF), whereas the inference engine obtains the output terms according to the input terms from the fuzzifier and the rule base. Finally, the defuzzifier converts the fuzzy inference results to a crisp value to present the decision. In other words, defuzzification is realized by a decision-making algorithm that selects the best crisp value based on a fuzzy set. In this work, the defuzzified value, X_{mom} is obtained using the mean of maximum (MOM) method since all operations in FIS-AES depends on the maximum value of RSSI. The X_{mom} obtained using MOM method is given as follows:

$$X_{mom} = \frac{\sum_{x_i \in M} x_i}{|M|}, \quad M = \{x_i \,|\mu_y(x_i) = \mu_{\max}\} \tag{5}$$

where X_{mom} is obtained when μ_{y} (x_{i}) reaches its maximum $\mu_{\max}$ and M is the cardinality .

To accommodate the three modes from each RPR antenna, the Pattern-MF is modeled by modifying the existing Gaussian-MF. The proposed Pattern-MF is provided as follows:

$$\mu(x) = a_{\text{mode\_II}} \exp^{\frac{(x_{\text{mode\_II}} - c_{\text{mode\_II}})^2}{2\sigma^2_{\text{mode\_II}}}} + a_{\text{mode\_I}} \exp^{\frac{(x_{\text{mode\_I}} - c_{\text{mode\_I}})^2}{2\sigma^2_{\text{mode\_I}}}} + a_{\text{mode\_III}} \exp^{\frac{(x_{\text{mode\_III}} - c_{\text{mode\_III}})^2}{2\sigma^2_{\text{mode\_III}}}} \tag{6}$$

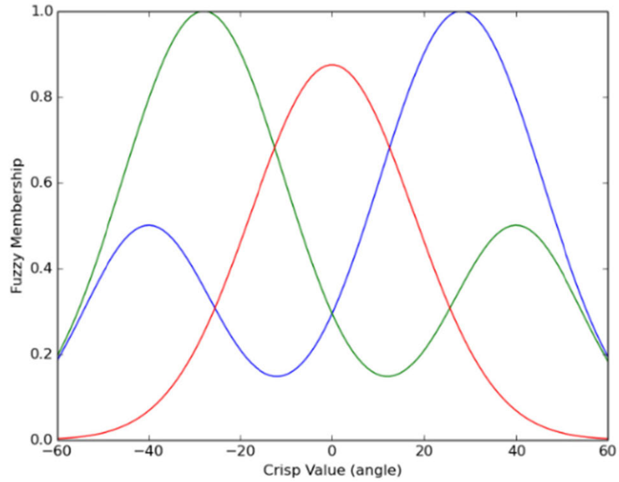

FIGURE 13. Proposed input membership function named as pattern-MF.

where $a_{\text{mode\_I}}, a_{\text{mode\_II}}$ and $a_{\text{mode\_III}}$ is the amplitude of the Pattern-MF from each RPR antenna; $c_{\text{mode\_I}}$, $c_{\text{mode\_II}}$ and $c_{\text{mode\_III}}$ represent the center of each Pattern-MF and $\sigma_{\text{mode\_I}}, \sigma_{\text{mode\_II}}$ and $\sigma_{\text{mode\_III}}$ is the width of each Pattern-MF. For modes II and III, it is expected that $c_{\text{mode\_II}} < c_{\text{mode\_I}}$ and $c_{\text{mode\_I}} < c_{\text{mode\_III}}$ so that the maximum value at the respective MF falls in $c_{\text{mode\_II}}$ and $c_{\text{mode\_III}}$. Important Gaussian-MF parameters such as $c_{\text{mode\_II}}$, $c_{\text{mode\_III}}, \sigma_{\text{mode\_II}}$ and $\sigma_{\text{mode\_III}}$ are optimized based on the radiation patterns from each proposed RPR antenna illustrated in Figure 7.

The proposed Pattern-MF is depicted in Figure 13. Each RPR consists of three input MFs as shown in Figure 13, thus a total of nine input MFs are available in the proposed FIS. It is expected that the proposed Pattern-MF (resulting from the modified Gaussian MF) will improve the AOA estimation by reducing the error. Apart from that, the proposed Pattern-MF is expected to reduce the overall system complexity, so that only three MFs are assigned for each RPR antenna for reasonably accurate estimation. In addition to that, if the number of beams from each RPR antenna is different from the three beams in this proposed system, optimization then needs to be performed according to the new number of beams and the maximum angles from each beam originating for each RPR antenna. This optimization will require that parameters c and σ of the Gaussian function to be adapted for use based on the new number and characteristics of the new beam patterns originating from each RPR antenna.

To ensure that the proposed Pattern-MF is useful for this AOA system, the radiation pattern of the RPR antenna is subdivided into five regions as shown in Figure 14 and Table 4. The five regions of the steering mode and angles covered by each RPR antenna are used for AOA estimation when adopting the FIS. Each region covers an area of approximately less than 30°, which decreases the potential of AOA estimation error. Adopting FIS by knowing the range of angle at each region, the AOA can be obtained by finding the smallest difference in ratio between the RPR antenna patterns

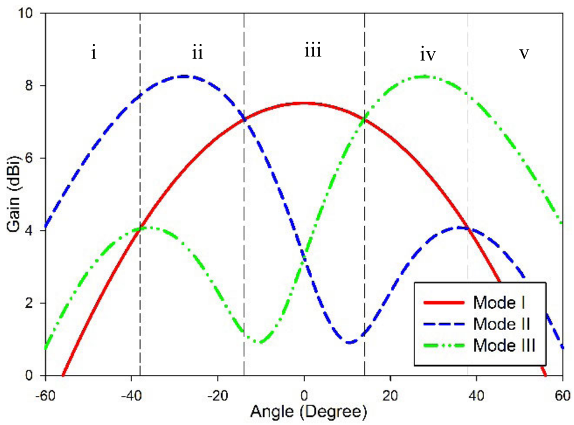

FIGURE 14. **The radiation patterns of the RPR antennas for all modes and regions determined by FIS.**

TABLE 4. **Region of RPR antennas with FIS.**

RPR Antenna	Region	Mode	Angle Covered
A	i	II	-60° to -38°
	ii	II	-37° to -15°
	iii	I	-14° to 15°
	iv	III	16° to 38°
	v	III	39° to 60°
B	i	II	61° to 82°
	ii	II	83° to 105°
	iii	I	106° to 135°
	iv	III	136° to 157°
	v	III	158° to 179°
C	i	II	-158° to -179°
	ii	II	-136° to -157°
	iii	I	-106° to -135°
	iv	III	-83° to -105°
	v	III	-61° to -82°

for the corresponding region, as illustrated in Figure 14. Figure 15 shows the working principle of the method based on the assumption that the maximum RSSI is received by RPR A in mode II.

The FIS can improve the decision making of the RF switches of the RPR antennas using selected fuzzy rules. The FIS-AES rules are applied to determine the regions of the AOA estimation, with the rules applied in each RPR antenna is summarized in Table 5. For instance, when RPR A is activated, i.e., the following rule (*R*) is applied:

***"IF**RPR A is ON and Input1 is Low or Mid and Input2 High and Input3 is Low or Mid **THEN** the Mode I RPR A is ON and the coverage region from $-14°$ to $15°$"*

As a result, the coverage region of the AOA estimation is obtained, and in the Raspberry-Pi, the related GPIO are triggered to activate the respective RF switches. Generally, each activated RPR antenna applies the same rules. For instance, for the case described in Figure 15, *R*3 (refer to Table 5) is applied.

However, the output of each rules is different due the variation of the initial location of each RPR antenna. For instance, when the FIS-AES rule No.3 is applied, the coverage area

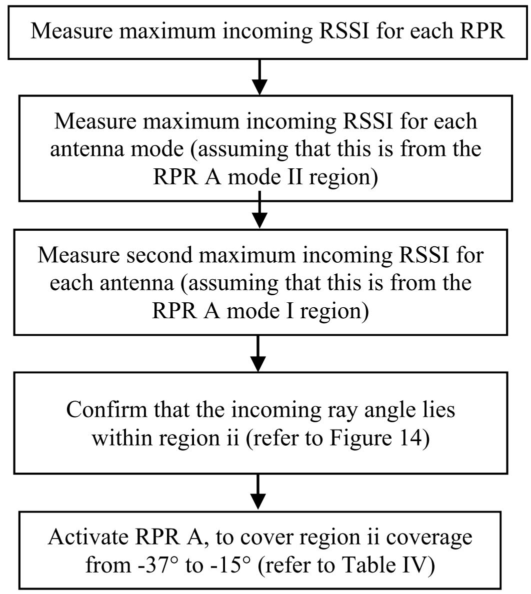

FIGURE 15. **The region verification process.**

TABLE 5. **Fuzzy rules for each activated RPR antenna.**

R	INPUT (BEAMS) Input 1	Input 2	Input 3	OUTPUT (ESTIMATION) RF-SW MODE	RPR A	RPR B	RPR C
1	High	Low	Mid	II	-60° to -38°	61° to 82°	-158° to -179°
2	High	Mid	Low	II	-37° to -15°	83° to 105°	-136° to -157°
3	Low/ Mid	High	Low/ Mid	I	-14° to 15°	106° to 135°	-106° to -135°
4	Low	Mid	High	III	16° to 38°	136° to 157°	-83° to -105°
5	Mid	Low	High	III	39° to 60°	158° to 179°	-61° to -82°

of the AOA estimation for the activated RPR antenna A is $-14°$ to $15°$, for RPR antenna B is $106°$ to $135°$, and for RPR antenna C is from $-106°$ to $-135°$. In other words, when each antenna is initially activated to scan the RSSI for the 360o coverage, these rules are applied and the related coverage regions are defined for each rule, depending on the activated antenna.

The unique feature of the proposed FIS-AES is its ability to scan additional AOA regions, especially when the edge region is covered using two RPR antennas. For instance, in the bordering region (v) for RPR A and region (i) for RPR B is estimated by the FIS based on the IF-THEN rule sets formulated by the fuzzy inference engine. The additional rules are presented in Table 6. An example rule is given as follows:

"IF RPR A is ON and Input1 is High at Mode II and RPR C is ON and Input3 is High at Mode III is High **THEN** the Mode II RPR A is ON and the region coverage $-61°$ to $-82°$"

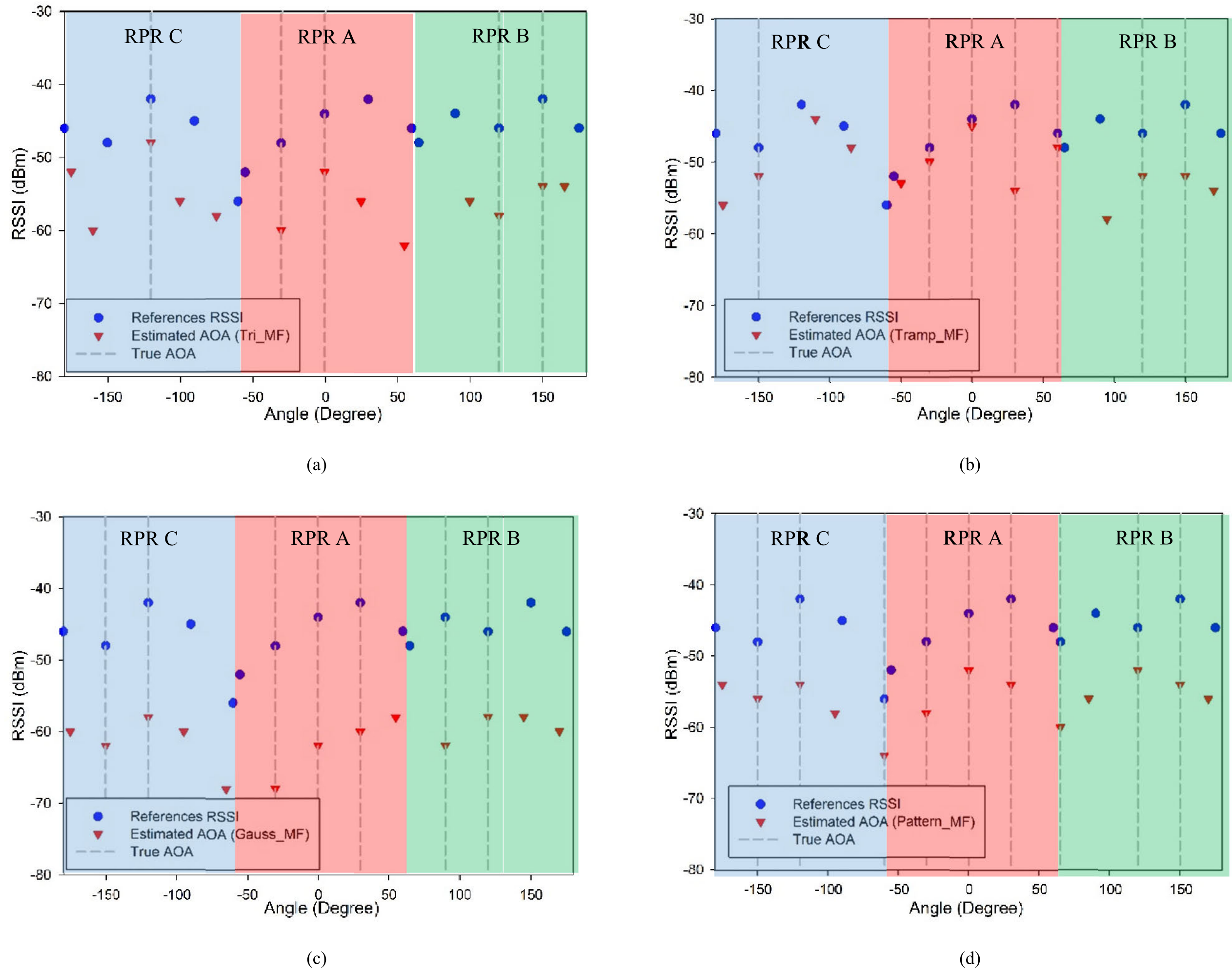

FIGURE 16. AOA Estimation adopted FIS vs reference AOA estimation. (a) Tri-MF. (b) Tramp-MF. (c) Gauss-MF. (d). Pattern-MF.

TABLE 6. Fuzzy rules for estimation between beam edges of two RPR antennas.

RULE	INPUT			OUTPUT	
	RPR C	RPR A	RPR B	RF-SW MODE	ESTIMATION
1	Input3 @Mode III	Input1 @Mode II	X	RPR A Mode II	-61° to -82°
2	X	Input3 @Mode III	Input1 @Mode II	RPR B Mode II	61° to 82°
3	Input1 @Mode II	X	Input3 @Mode III	RPR C Mode II	179° to -179°

The fuzzy rules are applied to the AOA estimation process to differentiate each region, as shown in Figure 16. Take note that each RPR consists of five regions with the use of FIS. The five regions are shown in Figure 14. To show the advantage of the proposed pattern MF, the FIS-AES system is also operated using Triangular MF (Tri-MF), Trapezoidal MF (Tramp-MF) and Gaussian MF (Gauss-MF). Figure 16(a) indicates that five AOA directions have been accurately detected by the AOA estimation with Tri-MF. The successfully detected AOAs are shown by the true AOAs line. The true AOA lines are drawn at the successful detection angle when the detected angle is similar for both maximum measured RSSI ($RSSI_{m\_max}$) and the maximum reference RSSI ($RSSI_{r\_max}$). All AOA estimations are compared with the reference AOA estimations that are illustrated in Figure 9. Using similar approach, seven accurate AOA estimations were achieved by the Tramp-MF and Gauss-MF, respectively as shown in Figure 16(b) and 16(c). Finally, Figure 16(d) indicates that nine AOA directions were obtained by this AOA estimation method when applying Pattern-MF. It clearly shows that the proposed AES with Pattern-MF obtain the most accurate AOA estimation points. Further comparison is carried out in following section to indicate the performance of the proposed AOA estimation using Pattern-MF.

VI. RESULT AND DICUSSION

This section compares the AOA estimation result with reference at a distance of 3m to obtain estimation error and estimation root-mean-square error (RMSE). Whenever required,

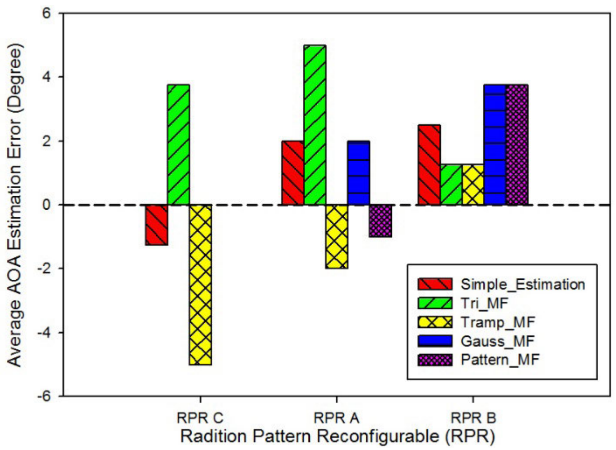

FIGURE 17. Experimental average of the AOA estimation absolute error result.

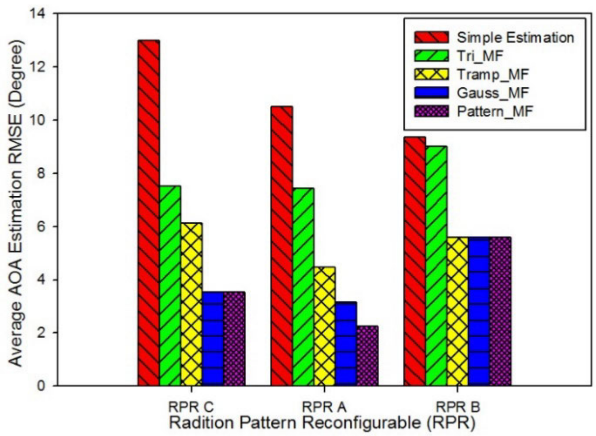

FIGURE 18. Experimental average of the AOA estimation RMSE result.

a simple linear interpolation is used to determine both parameters. Figure 17 shows the average AOA estimation error for each RPR antenna. For instance, RPR C which provides coverage from 60° to 180° shows no AOA estimation error for both Gauss-MF and Pattern-MF. The average estimation error for $n = 10$ is obtained using the following:

$$Avg\_e_{AOA} = \frac{1}{n}\sum_{m,r=1}^{n} \theta_{RSSI_{m\_\max}} - \theta_{RSSI_{r\_\max}} \tag{7}$$

where θ_{RSSI}m_max and θ_{RSSI}r_max is the angle at the RSSI$_{\text{m_max}}$ and RSSI$_{\text{r_max}}$, respectively. The measurement is repeated for the 360° angles enclosed by all three RPRs.

To show the error performance clearly, average RMSE is calculated for the AOA estimation. Figure 18 shows the overall RMSE comparison between all the AOA estimation schemes for each RPR antenna, which is calculated as follows:

$$Avg\_RMSE = \sqrt{\frac{1}{n}\sum_{m,r=1}^{n}\left(\theta_{RSSI_{m\_\max}} - \theta_{RSSI_{r\_\max}}\right)^2} \tag{8}$$

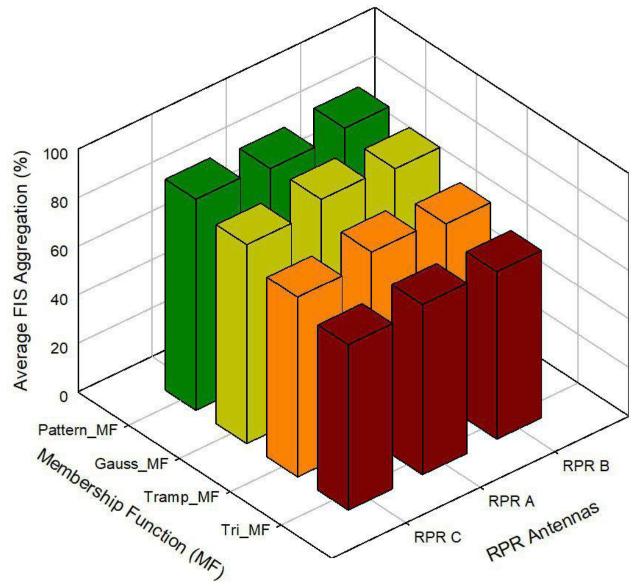

FIGURE 19. Experimental comparison of the FIS aggregation MF for each RPR antenna.

The simple AOA estimation method will result in the highest RMSE value. This is due to the wide angle that needs to be covered, resulting in a small number of accurate AOA estimations. Note that such simple AOA estimation is able to work without the assistance of FIS, as it selects the AOA based on the maximum received RSSI, as explained in Section IV. Thus, it has only nine AOA estimation points. Through the analysis conducted in this work, it could be noticed that adopting the FIS algorithm, the RMSE value achieved below 10° for all types of MFs. Specifically, the FIS constructed using the modified Gaussian-MF or Pattern-MF yields the lowest error for all RPR antennas, thus considered to be the most accurate.

Figure 19 depicts FIS aggregation for all trained MF. The Tri-MF shows the lowest aggregation of between 60% and 70%. Aggregation of FIS is increased to 70% to 75% and 75% to 80% by applying Tramp-MF and Gauss-MF. Although FIS using conventional MF was able to improve the FIS aggregation, the proposed MF in this work exclusively further enhances the FIS aggregations. This can be validated when the Pattern-MF successfully achieved the maximum FIS aggregation of between 80% and 85%. This is due to the algorithm which is developed based on Gauss-MF and inspired by radiation pattern of RPR antenna.

Table 7 summarizes the performances of the available AOA estimation using RSSI-based approaches. It can be noticed that most previous approaches achieved 360° coverage with the use of mechanical assistance. This may result in high power consumption of the mechanical components, the need of regular maintenance of the rotary system and beam scanning speed limitation. In contrast, the approach proposed in this work reduced the required number of antennas to provide 360° coverage for AOA estimation. Most importantly,

TABLE 7. Comparison of the proposed AoA estimation method using RSSI with previous researches.

Research By	Type	Complexity	Angle Estimation	Algorithm
[19]	Electronic	Low	12 angle estimation	No
[33]	Electronic	High	4 different angles	No
[13]	Mechanical	High	(Full) 360°	No
[34]	Mechanical	High	(Full) 360°	No
[35]	Mechanical	High	(Full) 360°	No
[36]	Electronic	Low	4 different angles	No
[12]	Electronic	High	(Full) 360°	Yes
Proposed AES	Electronic	Low	(Full) 360°	Yes

the proposed work also integrates for the first time, RPR antennas with the FIS to result in a more accurate AOA estimation.

It is important to note that the proposed system has only been assessed for scenarios with line of sight (LOS) incidence. For non-LOS (NLOS) environment, it is expected that the proposed RPR system will still steer the beam to towards the direction where it receives the strongest RSSI, regardless of the type of incident waves (including waves from reflections). Thus, the estimated angle will consistently depend on the direction where the strongest RSSI is originating from.

VII. CONCLUSION

An AOA estimation system based on incoming RSSI is presented in this paper. The system is able to estimate AOA using 15 AOA regions with only using three sets of radiation pattern reconfigurable antennas. Each RPR antennas is controlled by a RF-PIN diode as switch. The proposed AOA estimation system using FIS is capable of increasing the number of AOA estimation points and consequently minimize estimation errors, to less than 10° for all MF. For this AOA system with three RPR antennas, a new Pattern-MF is introduced to increase percentage of response between the input (fuzzifier) and the output (defuzzifier) in FIS. Approximately 80% to 85% FIS aggregation is obtained by Pattern-MF, which is the highest compared to the existing MF. The accuracy of this proposed system only is comparable with AOA estimation systems which adopts pattern reconfigurable antennas, switchable antennas and multiple antennas. In the current work, there are 15 estimation regions, indicating that its resolution is limited to approximately 30°. This can be considerably improved by applying RPR antennas with more than three switchable main beams in the radiation pattern, and by modifying their corresponding Pattern-MF to further enhance the overall AES performance.

ACKNOWLEDGMENT

The authors would like to thank the members of the Embedded Network and Communication (ENAC) research cluster, Universiti Malaysia Perlis (UniMAP) for their technical assistance in completing this work.

REFERENCES

[1] P. Kułakowski, J. Vales-Alonso, E. Egea-López, W. Ludwin, and J. García-Haro, "Angle-of-arrival localization based on antenna arrays for wireless sensor networks," *Comput. Electr. Eng.*, vol. 36, no. 6, pp. 1181–1186, Nov. 2010.

[2] M. Malajner, D. Gleich, and P. Planinšič, "Angle of arrival estimation algorithms using received signal strength indicator," *Electron. Compon. Mater.*, vol. 45, no. 4, pp. 237–248, Jan. 2015.

[3] J. Zhou, H. Zhang, and L. Mo, "Two-dimension localization of passive RFID tags using AOA estimation," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf.*, May 2011, pp. 511–515.

[4] J.-R. Jiang, C.-M. Lin, F.-Y. Lin, and S. T. Huang, "ALRD: AoA localization with RSSI differences of directional antennas for wireless sensor networks," *Int. J. Distrib. Sensor Netw.*, vol. 9, no. 3, Mar. 2013, Art. no. 529489.

[5] X. Huang and Y. J. Guo, "Wideband AoA estimation and beamforming with hybrid antenna array," in *Proc. IEEE Global Telecommun. Conf. GLOBECOM*, Dec. 2011, pp. 1–6.

[6] N. H. Noordin, T. Arslan, B. W. Flynn, A. T. Erdogan, and A. O. El-Rayis, "Single-port beamforming algorithm for 3-faceted phased array antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 813–816, 2013.

[7] X. Huang, Y. J. Guo, and J. Bunton, "Adaptive AoA estimation and beamforming with hybrid antenna arrays," in *Proc. IEEE 70th Veh. Technol. Conf. Fall*, Sep. 2009, pp. 1–5.

[8] R. Sanudin, N. H. Noordin, A. O. El-rayis, N. Haridas, A. T. Erdogan, and T. Arslan, "Capon-like DOA estimation algorithm for directional antenna arrays," in *Proc. Loughborough Antennas Propag. Conf.*, Nov. 2011, pp. 1–4.

[9] N. A. A. Elhag, I. M. Osman, A. A. Yassin, and T. B. Ahmed, "Angle of arrival estimation in smart antenna using MUSIC method for wideband wireless communication," in *Proc. Int. Conf. Comput., Electr. Electron. Eng. (ICCEEE)*, Aug. 2013, pp. 69–73.

[10] A. Bazzi, D. T. M. Slock, L. Meilhac, and S. Panneerselvan, "A comparative study of sparse recovery and compressed sensing algorithms with application to AoA estimation," in *Proc. IEEE 17th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Jul. 2016, pp. 1–5.

[11] L. Zhang, Y. H. Chew, and W.-C. Wong, "Precoder design for improving the performance of MUSIC-based angle-of-arrival estimator," in *Proc. IEEE 22nd Int. Symp. Pers., Indoor Mobile Radio Commun.*, Sep. 2011, pp. 1294–1298.

[12] M. Malajner, D. Gleich, and P. Planinšič, "Angle of arrival measurement using multiple static monopole antennas," *IEEE Sensors J.*, vol. 15, no. 6, pp. 3328–3337, Jun. 2015.

[13] C. Park, D. Park, J. Park, Y. Lee, and Y. An, "Localization algorithm design and implementation to utilization RSSI and AOA of zigbee," in *Proc. 5th Int. Conf. Future Inf. Technol.*, May 2010, pp. 1–4.

[14] J. Graefenstein, A. Albert, P. Biber, and A. Schilling, "Wireless node localization based on RSSI using a rotating antenna on a mobile robot," in *Proc. 6th Work. Positioning, Navig. Commun.*, Mar. 2009, pp. 253–259.

[15] M. I. Jais, P. Ehkan, R. B. Ahmad, I. Ismail, T. Sabapathy, and M. Jusoh, "Review of angle of arrival (AOA) estimations through received signal strength indication (RSSI) for wireless sensors network (WSN)," in *Proc. Int. Conf. Comput., Commun., Control Technol. (I4CT)*, Apr. 2015, pp. 354–359.

[16] S. Maddio, A. Cidronali, and G. Manes, "An azimuth of arrival detector based on a compact complementary antenna system," in *Proc. 3rd Eur. Wireless Technol. Conf.*, Sep. 2010, pp. 249–252.

[17] Z. Cao, H. P. A. van den Boom, R. Lu, Q. Wang, E. Tangdiongga, and A. M. J. Koonen, "Angle-of-arrival measurement of a microwave signal using parallel optical delay detector," *IEEE Photon. Technol. Lett.*, vol. 25, no. 19, pp. 1932–1935, Oct. 1, 2013.

[18] W. Zhang, Q. Yin, H. Chen, F. Gao, and N. Ansari, "Distributed angle estimation for localization in wireless sensor networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 2, pp. 527–537, Feb. 2013.

[19] M. R. Kamarudin, Y. I. Nechayev, and P. S. Hall, "Onbody diversity and angle-of-arrival measurement using a pattern switching antenna," *IEEE Trans. Antennas Propag.*, vol. 57, no. 4, pp. 964–971, Apr. 2009.

[20] M. Z. Win and Y. Shen, "On the accuracy of localization systems using wideband antenna arrays," *IEEE Trans. Commun.*, vol. 58, no. 1, pp. 270–280, Jan. 2010.

[21] M. Abusultan, S. Harkness, B. J. Lameres, and Y. Huang, "FPGA implementation of a Bartlett direction of arrival algorithm for a 5.8 Ghz circular antenna array," in *Proc. IEEE Aerosp. Conf.*, Mar. 2010, pp. 1–10.
[22] R. Zekavat and R. Michael Buehrer, *Handbook of Position Location: Theory, Practice and Advances*, 1st ed. New York, NY, USA: Wiley, 2012.
[23] K. A. Gotsis, K. Siakavara, and J. N. Sahalos, "On the direction of arrival (DoA) estimation for a switched-beam antenna system using neural networks," *IEEE Trans. Antennas Propag.*, vol. 57, no. 5, pp. 1399–1411, May 2009.
[24] T. Sabapathy, M. F. B. Jamlos, R. B. Ahmad, M. Jusoh, M. I. Jais, and M. R. Kamarudin, "Electronically reconfigurable beam steering antenna using embedded RF PIN based parasitic arrays (ERPPA)," *Prog. Electromag. Res.*, vol. 140, pp. 241–261, 2013.
[25] M. Jusoh, M. F. B. Jamlos, M. R. Kamarudin, M. F. A. Malek, M. A. Romli, Z. A. Ahmad, M. H. Mat, and M. S. Zulkefli, "A reconfigurable ultrawideband (UWB) compact tree-design antenna system," *Prog. Electromagn. Res. C*, vol. 30, no. June, pp. 131–145, 2012.
[26] D. Pujara, A. Modi, N. Pisharody, and J. Mehta, "Predicting the performance of pyramidal and corrugated horn antennas using ANFIS," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 293–296, 2014.
[27] S. Bandyopadhyay, H. Mistri, P. Chattopadhyay, and B. Maji, "Antenna array synthesis by implementing non-uniform amplitude using Tsukamoto fuzzy logic controller," in *Proc. Int. Conf. Adv. Electron. Syst. (ICAES)*, Sep. 2013, pp. 19–23.
[28] J. B. Krishna, P. Parvathi, and N. Latha, "Adaptive neuro fuzzy inference system for the optimization of behavior of fractal antenna," in *Proc. Int. Conf. Commun., Devices Intell. Syst. (CODIS)*, Dec. 2012, pp. 242–245.
[29] M. Tayel, N. E. D. H. Ismail, and H. D. Ramadan, "Neuro-fuzzy design of phased array applicators for microwave hyperthermia," in *Proc. 23rd Nat. Radio Sci. Conf. (NRSC)*, Mar. 2006, pp. 1–8.
[30] J. Zhao and B. K. Bose, "Evaluation of membership functions for fuzzy logic controlled induction motor drive," in *Proc. IEEE 28th Annu. Conf. Ind. Electron. Soc.*, vol. 1, Nov. 2002, pp. 229–234.
[31] I. A. Hameed, "Using Gaussian membership functions for improving the reliability and robustness of students' evaluation systems," *Expert Syst. Appl.*, vol. 38, no. 6, pp. 7135–7142, Jun. 2011.
[32] F. Xiufang, G. Zhanqiang, Y. Mian, and X. Shibo, "Fuzzy distance measuring based on RSSI in wireless sensor network," in *Proc. 3rd Int. Conf. Intell. Syst. Knowl. Eng.*, vol. 1, Nov. 2008, pp. 395–400.
[33] M. F. Jamlos, T. B. A. Rahman, M. R. Bin Kamarudin, P. Saad, M. A. Shamsudin, and A. M. M. Dahlan, "A novel adaptive Wi-Fi system with RFID technology," *Prog. Electromagn. Res.*, vol. 108, no. July, pp. 417–432, 2010.
[34] B. N. Hood and P. Barooah, "Estimating DoA from radio-frequency RSSI measurements using an actuated reflector," *IEEE Sensors J.*, vol. 11, no. 2, pp. 413–417, Feb. 2011.
[35] M. Malajner, Ž. Čučej, and D. Gleich, "Angle of arrival estimation using a single omnidirectional rotatable antenna," in *Proc. IEEE Int. Conf. Wireless Inf. Technol. Syst.*, Nov. 2012, pp. 1–4.
[36] A. U. Ahmed, M. T. Islam, and M. Ismail, "Estimating DoA from radio frequency RSSI measurements using multi-element Femtocell configuration," *IEEE Sensors J.*, vol. 15, no. 4, pp. 2087–2092, Apr. 2015.

MOHD ILMAN JAIS received the bachelor's and master's degrees (Hons.) majoring in communication engineering from Universiti Malaysia Perlis (UniMAP), Malaysia, in 2011 and 2014, respectively, where he is currently pursuing the Ph.D. degree in computer engineering. His research interests include reconfigurable antennas, fuzzy inference systems, embedded systems, and the Internet of Things.

THENNARASAN SABAPATHY received the B.Eng. degree in electrical telecommunication engineering from Universiti Teknologi Malaysia, in 2007, the M.Sc.Eng. degree from Multimedia University, Malaysia, in 2011, and the Ph.D. degree in communication engineering from University Malaysia Perlis, in 2014. In 2007, he has served as the Test Development Engineer with Flextronics, working on hardware and software test solutions for mobile phone manufacturing. Then, he was a Research Officer with Multimedia University, from 2008 to 2010, while pursuing the M.Eng.Sc. degree. From 2012 to 2014, he was a Research Fellow of University Malaysia Perlis during the Ph.D. degree. He is currently a Senior Lecturer with the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis. His current research interests include antenna and propagation, millimeter-wave wireless communications, and fuzzy logic for wireless communications.

MUZAMMIL JUSOH received the bachelor's degree in electrical-electronic and telecommunication engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia (UTM), in 2006 and 2010, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013. He was with the Department of Civil Aviation (DCA), TUDM, PDRM, ATM, Tanjong Pelepas Port (PTP), MCMC, and JPS (Hidrologi Department). He is currently supervising a number of Ph.D. and M.Sc. students. He is currently an Associate Professor and a Researcher with the School of Computer and Communication Engineering (SCCE), UniMAP. He is managing few grants under the Ministry of Higher Education Malaysia. He was an RF and Microwave Engineer with Telekom Malaysia Berhad (TM) Company, from 2006 to 2009, where he was also the Team Leader of the Specialized Network Services (SNS) Department based in TM Senai Johor. He does preventive and corrective maintenance of ILS, NDB, DVOR, repeaters, microwave systems, VHF, and UHF based on contract wise. He holds an H-Index of 13 (SCOPUS). He has published over 132 technical articles in journals and proceedings including IEEE ACCESS, the IEEE ANTENNA AND WIRELESS PROPAGATION LETTER (AWPL), *Microwave and Optical Technology Letter* (MOTL), the *International Journal on Antenna and Propagation* (IJAP), *Progress in Electromagnetics Research* (PIER), and *Radio Engineering* journal and more than 50 conference papers. His research interests include antenna design, reconfigurable beam steering antennas, wearable antennas, MIMO, UWB, wireless on-body communications, in-body communications (implantable antenna), wireless power transfer, and RF and microwave communication systems. Moreover, he is a member of the IET (MIET), the Antenna and Propagation Society (AP/MTT/EMC), and the Malaysia Chapter. He has received the Chartered Engineering Certification, in July 2017.

R. BADLISHAH AHMAD received the B.Eng. (Hons.) in electrical and electronic engineering from Glasgow University, in 1994, and the M.Sc. degree in optical electronic engineering and the Ph.D. degree from the University of Strathclyde, in 1995 and 2000, respectively. His research interests include computer and telecommunication network modelling using discrete event simulators, optical networking, and embedded systems based on GNU/Linux.

MOHD HAIZAL JAMALUDDIN received the bachelor's and master's degrees in electrical engineering from Universiti Teknologi Malaysia (UTM), Malaysia, in 2003 and 2006, respectively, and the Ph.D. degree in signal processing and telecommunications from the Université de Rennes 1, France, in 2009, with a focus on microwave communication systems and specially antennas such as dielectric resonators, and reflectarray and dielectric dome antennas. He is currently an Associate Professor with the Wireless Communication Centre, School of Electrical Engineering, Universiti Teknologi Malaysia. He has published more than 100 articles in reputed indexed journals and conference proceedings. His research interests include dielectric resonator antennas, printed microstrip antennas, MIMO antennas, and reflectarray antennas.

MUHAMMAD RAMLEE KAMARUDIN (M'08–SM'13) received the degree (Hons.) in electrical and telecommunication engineering from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 2003, and the M.Sc. degree in communication engineering and the Ph.D. degree in electrical engineering from the University of Birmingham, Birmingham, U.K., in 2004 and 2007, respectively, under the supervision of Emeritus Prof. P. Hall. He has been an Associate Professor with the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, since May 2019. Prior to this appointment, he was a Senior Lecturer with the Centre for Electronic Warfare, Information and Cyber, Cranfield Defense and Security, Cranfield University, U.K., and an Associate Professor with the Wireless Communication Centre, Universiti Teknologi Malaysia. He holds a SCOPUS H-Index of 23 with over 2000 citations. He has authored a book chapter of a book entitled *Antennas and Propagation for Body-Centric Wireless Communications*. He has published over 240 technical articles in leading journals and international proceedings including the IEEE TRANSACTION ON ANTENNAS AND PROPAGATION, the IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, the *IEEE Antenna Magazine*, IEEE ACCESS, the *International Journal of Antennas and Propagation*, *Progress in Electromagnetic Research*, *Microwave and Optical Technology Letters*, and *Electronics Letters*. His research interests include antenna design for 5G/6G, MIMO antennas, array antenna for beam-forming and beam steering, wireless on-body communications, in-body communications (implantable antenna), RF and microwave communication systems, and antenna diversity. He is a member of the IET, an Executive Member of the Antenna and Propagation Society, and Malaysia Chapter, and a member of the IEEE Antennas and Propagation Society, the IEEE Communication Society, the IEEE Microwave Theory and Techniques Society, and the IEEE Electromagnetic Compatibility Society. He was an Associate Editor of *Electronics Letters* and *IET Microwaves, Antennas and Propagation*, and an Academic Editor of the *International Journal of Antennas and Propagation*.

PHAKLEN EHKAN received the B.Eng. degree in electrical engineering from Universiti Teknologi Malaysia (UTM), the M.Sc. degree in Information Technology from UUM, and the Ph.D. degree in computer engineering from Universiti Malaysia Perlis. He was an Engineer in electronic industries for six years. He joined the School of Computer and Communication Engineering, Universiti Malaysia Perlis, as a Lecturer, in 2003. He has published over 80 articles in international journals and proceedings. His current research interests include reconfigurable computing and FPGA, digital design, and embedded systems, digital and image processing, system on chip (SoC), smart systems, and the IoT. He is currently a chartered engineer in U.K. and a member of BCS and IACSIT.

L. MURUKESAN LOGANATHAN received the B.E. and M.Sc. degrees in mechatronic engineering from the Universiti Malaysia Perlis (UniMAP), Malaysia, in 2012 and 2015, respectively, where he is currently pursuing the Ph.D. degree in computer engineering under the supervision of Dr. T. Sabapathy. His research interest includes the development of energy efficient medium access control (MAC) protocols for the internet of things and wireless sensor networks.

PING JACK SOH (S'10–M'14–SM'15) was born in Sabah, Malaysia. He received the B.Eng. and M.Eng. degrees from Universiti Teknologi Malaysia and the Ph.D. degree from the ESAT-TELEMIC Research Division, KU Leuven, Belgium.

He is currently an Associate Professor with the School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), and a Research Affiliate with KU Leuven. From 2002 to 2004, he was a Test Engineer with Venture Corp. In 2005, he joined Motorola Solutions Malaysia, as a Research Development Engineer. Since 2006, he has been a Lecturer with UniMAP before pursuing the Ph.D. degree with the ESAT-TELEMIC Research Division, KU Leuven, as a Research Assistant, from 2009 to 2013. He was also a Postdoctoral Fellow with KU Leuven, from 2013 to 2014. He studies actively in his areas of interest, including wearable and flexible antennas/metasurfaces, on-body communication, electromagnetic safety and absorption, and wireless and radar techniques for healthcare applications.

Dr. Soh is a member of the IET and URSI. He is a registered Chartered Engineer with the U.K. Engineering Council and a registered Professional Technologist with the Malaysia Board of Technologist (MBOT). He also serves on the IEEE MTT-S Education Committee and the IEEE MTT-S Meetings and Symposia (M&S) Committee. He was a recipient of the IEEE APS Doctoral Research Award, in 2012, the IEEE MTT-S Graduate Fellowship for Medical Applications, in 2013, and the URSI Young Scientist Award, in 2015. He was also the Second Place Winner of the IEEE President's Change the World Competition, in 2013.