A Narrow Beam Steering Antenna Array for Indoor Positioning Systems Based on Wireless Sensor Network

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ABSTRACT This paper proposes the 2.45 GHz planar Beam Steering Antenna Array for Indoor Positioning Systems. The antenna array consists of a phase shifter based on a 4 × 4 Butler matrix, and an array of four dipole Yagi antennas. By choosing one of four beams using a switching controller, the main beam of the antenna can steer in four directions from +37°, −12°, +12° to −36°. The antenna has a narrow fan beam with a beamwidth in the azimuth plane of from +21.5° to +24.5° and in the elevation plane of approximately 90° which effectively minimizes multipath signals. These advantages are suitable for positioning systems to increase location accuracy. The antenna achieves a peak gain of from 9.1 to 9.8 dBi in four directions, a wide band of 400 MHz. The fully electronically steerable antenna prototype has been designed using CST software, simulated based on the finite element method, and fabricated on the RO4003C substrate as well as measured. The antenna is implemented in the Indoor Positioning System using three different location methods, including trilateration, triangulation, and fingerprinting, to highlight the antenna’s advantages in improving location accuracy with the ratio between the mean location error and area of 0.051, 0.033, and 0.023 respectively.

INDEX TERMS Printed dipole Yagi, hybrid coupler antenna array, Butler matrix, beam steering antenna, indoor positioning.

I. INTRODUCTION Positioning System (PSs) based on Wireless Sensor Network (WSN) have become more popular with advantages such as low cost, low power consumption, easy implementation, and expansion of systems. They have many applications in various fields such as healthcare, tracking, IoT, and Smart Transportation [1]. However, the challenges of location systems based on WSN are an increase in localization accuracy and system stability as well as a decrease in response time and system complexity [2]. Antennas used in these systems play an important role in the improvement of positioning accuracy. Traditionally, antennas used in positioning systems are usually omni antennas which have their pros and cons at the same time. The advantage is that they can receive signals from all directions, while the disadvantages of using omni antennas in PSs are that they give a low localization accuracy, complexity processing, and a high risk of network congestion [3]. Using Beam Steering Antenna Arrays (BSAAs) with narrow beamwidth is a good solution to resolve the limitations mentioned above. To increase the localization accuracy of PSs, the beamwidth in the sweep plane is as narrow as possible. However, obtaining the narrow beamwidth makes the antenna array more complicated due to a requirement of a large number of elements. For PSs based on WSN using ZigBee at 2.45 GHz, the element number of the antenna array should be four because of a balance between antenna array size and beamwidth. In [4], the antenna using four patch elements still has a wide beamwidth of from 60° to approximately 90°. The antenna in [5] and [6] with a narrow beamwidth in the sweep plane, can help to obtain a high localization accuracy. Nevertheless, the peak gain of the antenna in [5] is low, which is only from 3.94 to 6.11 dBi. In [6], the wide beamwidth in the orthogonal plane leads to...
multipath fading due to reflection from the ground surface when used in the triangulation. In this paper, a BSAA for Zigbee based PSs operating at 2.45 GHz was proposed. The antenna is composed of a switch SP4T, a phase shifter, and a dipole-Yagi antenna array. The BSAA achieves four fan beams with a narrow beamwidth from 21.5° to 24.5° in the elevation plane and a suitable beamwidth of approximately 90° in the azimuth plane. Besides, the other advantages of the proposed antenna are that it has a wide bandwidth, high efficiency, and a planar structure. The antenna with a narrow beamwidth helps to increase positioning accuracy in PSs. To highlight this antenna’s advantage in improving location accuracy, the BSAA is integrated into three fixed nodes in the Zigbee-based Indoor Positioning System in the space with a mean error of 1 m and a position accuracy of 90 mm. When a port is selected, a beam direction is steered. Consequently, the antenna beam can be steered in different directions.

II. ANTENNA ARRAY DESIGN
The BSAA consists of the components as shown in Fig.1, including a phase shifter, a dipole array, and a switching controller. The phase-shifter based on the 4 × 4 Butler matrix was integrated with an array of four dipole antenna elements on a Roger substrate. The antenna beam is steered in four directions from −36°, −12°, +12° to +37°. The antenna has a narrow fan beam with a beamwidth in the azimuth plane from 21.5° to 24.5°. When a port is selected, a beam direction is steered. Consequently, the antenna beam can be steered in different directions.

![Schematic of the BSAA.](image)

The angle of the antenna main beam, θ, is according to equation (2) [7].

\[
\theta = \arccos \left( \frac{-\Delta \phi}{kd} \right) \tag{2}
\]

where \( k = 2\pi \lambda \) is the wave-number, and \( d \) is the distance between two neighboring elements in the antenna array. The antenna array is composed of four dipole antennas arranged linearly with \( d = 0.57l \) to enhance gain and reduce mutual coupling.

A. PRINTED DIPOLE ANTENNA ELEMENT
This section presents a design of antenna element, which is a microstrip dipole-Yagi antenna, for Zigbee standard at 2.45 GHz. The structure of the antenna element with a driver, directors, and a J-balun is shown in Fig.2. The Fig.3 shows the prototype which was fabricated on RO4003C substrate with \( \varepsilon_r = 3.55 \) and \( h = 0.8 \text{ mm} \). By improving the J balun-fed, a wideband balun-fed is integrated into the antenna to obtain a wideband printed one. The driver of the antenna consists of two arms. These arms are folded to reduce their sizes. Two parallel bars as directors are added to the dipole to obtain a directional radiation pattern and to increase its gain. The antenna size is 74 mm × 57 mm × 0.8 mm with the detailed dimension are presented in Table 1. The design steps are similar to our previous work in [6]. The antenna obtains a gain of 6.4 dBi at 2.45 GHz and a bandwidth of 240 MHz.

![Printed dipole-Yagi antenna.](image)

B. 4 × 4 BUTTLER MATRIX DESIGN
Fig.4 shows the model of the 4 × 4 Butler matrix, which has been presented in [6], including four 90° couplers, including a phase shifter, a dipole array, and a switching controller. The phase-shifter based on the 4 × 4 Butler matrix was integrated with an array of four dipole antenna elements on a Roger substrate. The antenna beam is steered in four directions from −36°, −12°, +12° to +37°. The antenna has a narrow fan beam with a beamwidth in the azimuth plane from 21.5° to 24.5°. When a port is selected, a beam direction is steered. Consequently, the antenna beam can be steered in different directions.

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C. ANTENNA RESULTS AND DISCUSSIONS

The prototype of the antenna was fabricated as depicted in Fig.6. Fig.8 demonstrates the simulation and measurement reflection coefficients at four antenna feedings. It can be seen that the antenna has a good impedance match in the operating bandwidth, from 2.32 GHz to 2.72 GHz. The simulation and measurement results are well matched. Fig. 9 shows the BSAA measurement setup in the anechoic chamber, and Fig. 10 shows the simulation and measurement 2D radiation pattern.

Table 2 shows the comparison between the proposed antenna array and other antennas in the related works having the same operating frequency, antenna element number, and phase shifter type. The advantage of the proposed antenna is that the fan beamwidth is narrow in xoy plane, from 21.5° to 24.5°, which can help to improve localization accuracy in PSs. The peak gains of the four directions are from 9.1 dBi to 9.8 dBi, higher than the ones in [5], [6], [9], and [10] except for [8]. It is because the radiation beam in [8] is a...
pencil beam (PB) that is more directional than a fan beam, and the loss tan of antenna substrate in [8] (Duroid 5880) is three times lower than that in the proposal (RO4003C). The sweep angles of the proposed BSAA are $-36^\circ$, $-12^\circ$, $+12^\circ$, $+37^\circ$, so the sweep range is $97^\circ$. The beamwidth in the yoz plane is approximately $90^\circ$. The suitable beamwidth in this plane can bring several advantages, including (1) covering different highs of objects that the antenna using patch elements cannot do, (2) avoiding reflection from floors or ceilings that is improved compared to the antenna in [8]. The antenna achieves a coefficient of over 80% and a wide bandwidth of 400 MHz (16.3 %). To obtain good performance with a suitable beamwidth and high efficiency in a planar construction, the tradeoff of the antenna is a horizontal linear array with an element-to-element distance of more than or equal to a half of the wavelength which leads to a large antenna dimension of $220 \text{ mm} \times 260 \text{ mm}$.

III. ANTENNA APPLICATION FOR INDOOR POSITIONING

A. SYSTEM CONFIGURATION

The system uses a configuration with three fixed nodes, namely node 1, node 2, and node 3, as shown in Fig.11. The proposal scenario is implemented in a space with the size of $10 \text{ m} \times 12 \text{ m} \times 5 \text{ m}$ in a building. The located objects, namely a mobile node, are in the standard grid with the size of $9 \times 9$ (81 points) and the mesh size of $0.5 \text{ m} \times 0.5 \text{ m}$. In this work, the location objects are focused on mobile devices that have a stable transmitted power such as service robots or mobile objects integrated with Zigbee nodes. These mobile nodes use the Zigbee standard at a frequency of $2.4 \text{ GHz}$ with a transmitted power of $18 \text{ dBm}$ in this scenario.

The fixed nodes consist of a receiver with a switching controller connecting to four inputs of the proposed BSAA as shown in Fig.6.
TABLE 2. Comparison to other antennas in the related works.

| @2.4GHz | [8] | [9] | [10] | [5] | [6] | Our work |
|---------|-----|-----|------|-----|-----|---------|
| Sweep angle (°) | -47.8 | 39 | -45 | -40 | -36 | -36 |
| | -14.3 | -12 | -15 | -20 | -12 | -12 |
| | +14.3 | +12 | +15 | +20 | +12 | +12 |
| | +47.8 | +40 | +45 | +40 | +37 | +37 |
| Beamwidth max E-plane (°) | 25.2 | 60 | 30 | 40.3 | 27 | 24.5 |
| Beamwidth max H-plane (°) | Narrow Beam | Narrow Beam | Narrow Beam | 240° | ≈ 90° |
| Peak gain (dBs) | 11.4 | [6.6, 11.8] | [6, 7.5] | [3.9, 6.1] | [7.9, 8.1] | [9.1, 9.8] |
| Bandwidth (MHz) | 200 | - | 600 | 100 | 531 | 400 |
| Efficiency | 90 % | - | 70 % | - | 88 % | 88 % |
| Structure | Planar | Non Planar | Non Planar | Planar | Planar |
| Dimension | 1.5 × 1.7 | - | 2.1 × 2.2 | 1.6 × 2.4 | 1.8 × 2.1 |

FIGURE 11. The coordinate system of the three-receiver trilateration method with test points in the center.

B. LOCATION METHOD

The configuration is implemented using three different methods including: (1) trilateration based on the Least Squares (LS) and the Bilateral Greed Iteration (BGI), (2) triangulation based on RSSI, and (3) fingerprinting based on WKNN algorithm to evaluate and compare the accuracy of the system corresponding to those three methods. The algorithm flowcharts of the three methods are presented in Fig.13, 14, 15. The system uses data from 81 points of the grid and 10 test points.

1) TRILATERATION METHOD

In radio propagation model, the received power is calculated according to equation (3).

\[ P_r(d) = P_r(d_0) - 10 \log \frac{d}{d_0} + X_b \] (3)

where \( P_r(d) \) and \( P(d_0) \) denote the received power at distance \( d \) and the reference point \( d_0 \), respectively, and \( n \) is the path loss factor, \( X_b \) is the effect due to obstacles such as walls, people and interlayers. In this implementation scenario, MRF24J40 microchip devices are integrated into transceiver nodes with RSSI values ranging from 0 − 255. According to the MRF24J40 data sheet, the relationship between RSSI values and the received power \( P_r \) at different distances is given by formula (4).

\[ P_r(d) = 0.2 \times \text{RSSI}(d) - 88 \text{[dBm]} \] (4)

The value of \( n \) and \( X_b \) are calculated corresponding to \( P_r(d) \) and \( P_r(d_0) \) which are based on the measured RSSI values.

In the implementation model, when \( d_0 = 1m \) and the different distance from transmitter to receiver in cases of \( d = 2m, 3m, 4m, 5m \), the average value of \( n \) and \( X_b \) are 4.3 and 3.4 respectively. Based on the value of received present power at nodes 1, 2, and 3, the trilateration method is applied to estimate the location of the object according to equation (5).

\[ d = d_0 \times 10^{[P_r(d_0) - P_r(d) + X_b] / 10} \] (5)

The LS [11] and BGI [12], [13] positioning algorithms are presented as Fig.13. The position coordinates of the three fixed nodes are \((x_1, y_1), (x_2, y_2), (x_3, y_3)\) and the location coordinate of the object is \((x, y)\). \( d_1, d_2, d_3 \) are estimated distances from node 1, 2, 3 to the object. \( A, X, b \) are the matrices according to equation (6).

\[ A \cdot X = b \] (6)

where

\[ A = \begin{bmatrix} 2(x_3 - x_1) & 2(y_3 - y_1) \\ 2(x_3 - x_2) & 2(y_3 - y_2) \end{bmatrix} \]

\[ b = \begin{bmatrix} d_1^2 - d_3^2 - x_1^2 + y_1^2 + x_3^2 + y_3^2 \\ d_2^2 - d_3^2 - x_2^2 - y_2^2 + x_3^2 + y_3^2 \end{bmatrix} \]

\[ X = \begin{bmatrix} x \\ y \end{bmatrix} \]
FIGURE 13. Algorithm of trilateration method based on LS and BGI.

The estimated object position, namely \( \hat{X} \) or \((\hat{x}, \hat{y})\), is solved from equation (6) based on the LS algorithm [14], [15].

\[
\hat{X} = (A^T A)^{-1} A^T b
\]  

Besides the LS algorithm, BGI is simple at positioning process and improves localization mean error [16]. The BGI algorithm with six steps is summarized as follows.

Step 1: Define three circles \( C_i, i = 1 \rightarrow 3 \), with their centers corresponding to the system’s node positions with coordinates \((x_i, y_i)\).

Step 2: Estimate the radius \( r_i \) of \( C_i \) to find the position point \( M_1 \). There are four different position relationships between \( C_i \) and \( C_{i+1} \) as presented in [12].

Step 3: Figure out two circles \( C_i \) and \( C_{i+1} \) to determine the first position point \( M_1(x_{M1}, y_{M1}) \) based on four different correlate positions between \( C_i \) and \( C_{i+1} \) as presented in [12].

Step 4: Determine the relationships between the third circle \( C_{i+2} \) and the first position point \( M_1 \) to define the second position point \( M_2(x_{M2}, y_{M2}) \). The line from \((x_3, y_3)\) to \( M_1 \) intersects the third circle at \( P \). \( M_2 \) is the center point of the line \( PM_1 \).

Step 5: Go on doing step 4 to find out \( M_i(x_{Mi}, y_{Mi}) \) until the rest of the circles.

Step 6: The final \( M_i \) represents the object’s estimated position, \( M_i(\hat{x}, \hat{y}) \).

2) TRIANGULATION METHOD

In this scenario, the RSSI max algorithm is applied to estimate the incoming wave direction [17] to find the location of the mobile node. This position is at the intersections of the incoming wave boundaries [18], [19]. The algorithm is presented as in Fig.14.

Based on the signal strength received via RSSI corresponding to each main beam of the proposed BSAA, the direction of arrival with the largest RSSI is the direction of the object. The object direction is a region that is the half-power beamwidth corresponding to the largest RSSI. This beamwidth of beam \( j \) in node \( i \) is determined by the angles...
$\alpha_{ij}$ and $\alpha_{ij}^2$ as demonstrated in Fig. 15. For example, the beam 2 of node 2 and the beam 3 of node 3 correspond to the largest RSSI values. In case of the largest RSSI values of two adjacent beams, beam $j$ and beam $j+1$ in node $i$, are equal or dissimilar with a light difference, Delta, the direction of arrival is formed by the main wave directions of the beam $j$, $\phi_{ij}$, and the beam ($j+1$), $\phi_{(j+1)i}$. For instance, in Fig. 15, the direction of arrival is created by the main wave direction of beam 2 and beam 3 of node 1. For Delta values less than 5, the error distribution function is obtained as shown in Fig. 16. It is shown that the error is the best when Delta = 3.

3) FINGERPRINTING METHOD

Indoor positioning based on Zigbee fingerprinting RSS (Received Signal Strength) has become a promising approach thanks to high performance. First, the offline localization stage is implemented. The RSSIs values of reference points on the $9 \times 9$ grid, 81 reference points were measured and stored as a database (see Fig.17). The mesh grid size is 0.5m with the row on the grid from A to I and the column on the grid from 1 to 9. Each reference point is measured by 50 samples for each beam of the four-beam antenna of a fixed node. We have $3 \times 4 \times (81 \times 40) = 38,880$ values of RSSI in total. Then data is sent to a computer that processes calculations and estimates the object’s location. Second, in the online localization stage, we have randomly picked 10 target positions represented by 10 red points in Fig. 17. In this subsection, we used Zigbee fingerprinting RSSI based on the weight K Nearest Neighbour algorithm (WKNN) to locate the target’s position. The target position is estimated by comparing the RSSI database and the measured RSS. Algorithm localization is presented in [19]. This method’s mean error is 0.75 m per area of 14 m$^2$. This method needs more time and more labor for the collection database in the offline phase.

C. LOCATION RESULTS

The PSs have been implemented with different methods to evaluate the location accuracy. The PS using trilateration based on BGI obtains the mean error of 1.64 m. For triangulation method based on $\text{RSSI}_{\text{max}}$, this parameter is 1.07 m. The PS using the fingerprinting method obtains the highest accuracy of 0.7 m. However, when the location environment changes, the database needs to be updated again, which is a limitation of the fingerprinting method. The advantages of the trilateration and triangulation methods are that they do not require building a big database. These two methods are suitable for PSs that do not need very high accuracy. Fig. 18 shows the cumulative distribution function of the PSs based on trilateration and triangulation methods when using omni antenna and BSAA. The location results of the PSs using proposal BSAA are shown in Table 3.

D. RELATED WORK AND COMPARISONS

This section presents the comparison in the accuracy of the PSs based on positioning methods, number of fixed nodes, and size of location spaces. For the fingerprint positioning method, the mean error depends on the mesh size, so the ratio between mean error and location area is used to evaluate and compare the location accuracy of the PSs. Table 4 shows the comparison in location results of the relevant publications and the PSs using the proposed antenna.

The table shows that the proposed PS has better accuracy than the publications [20], [21]. The PSs in [20] and [21] use isotropic antennas, which are significantly affected by multipath, causing large errors. The research in [22] and [24] have the advantage of simple configuration because the system only uses one node, but the positioning area cannot be expanded, so it can only be used in narrow rooms.

![FIGURE 16. Cumulative distribution function with different deltas for triangulation indoor PS.](image1)

![FIGURE 17. The typical illustration of fingerprinting IPS.](image2)

| Method           | Algorithm          | Mean Error | Min. Error | Max. Error |
|------------------|--------------------|------------|------------|------------|
| Trilateration    | LS BGI             | 1.67       | 0.545      | 3.36       |
| Triangulation    | $\text{RSSI}_{\text{max}}$ MUSIC | 1.07       | 0.04      | 3.46        | 11.20 |
| Fingerprinting   | WKNN (K=4)         | 0.75       | 0.11       | 1.90       |

TABLE 3. Mean error of the PSs using different location methods; unit: m.
TABLE 4. Comparison to the other PSs in the related works.

| Publications | Method          | Algorithm       | No. of Node | Antenna                  | Mean Error (m) | Area (m²) | Ratio between Mean and Error |
|--------------|-----------------|-----------------|-------------|--------------------------|----------------|-----------|-----------------------------|
| [20]; 2009   | Triangulation   | RSS$_{max}$     | 3           | BSAA (4 elements)        | 0.57           | 15        | 0.038                       |
| [21]; 2011   | Triangulation   | MinMax          | 3           | Omni                     | 2.58           | 32.26     | 0.080                       |
| [22]; 2013   | Triangulation   | ANN             | 1           | BSAA (3 elements)        | 0.99           | 28        | 0.035                       |
| [23]; 2015   | Triangulation   | SRB             | 4           | BSAA (7 elements)        | 0.63           | 9.88      | 0.064                       |
| [24]; 2017   | Fingerprinting  | KNN             | 1           | BSAA (10 elements)       | 0.85           | 34.55     | 0.0252                      |
| Our work     | Triangulation   | BGI             | 3           | BSAA (4 elements)        | 1.64           | 14        | 0.051                       |
|              | Fingerprinting  | RSS$_{max}$     |             |                          | 1.07           |           | 0.033                       |
|              | (Mesh grid: 0.5m) | WKNK            |             |                          | 0.75           |           | 0.023                       |

FIGURE 18. Cumulative distribution function for triangulation indoor PS based on triangulation and triangulation methods using omni and smart antenna.

The location accuracy in [23] is also higher than in the proposed PS, but the number of nodes in [20] is 4, which is larger than in the PS in our work. In [23], a location area expansion requires an increase in the number of nodes, while it is not necessary for the proposed PS. For the fingerprinting method, [24] uses SA radiated horizontally to both sides, so the system adds a screen at the back of the antenna to avoid causing a complicated multipath phenomenon that makes the PS complex. Based on the proposed antenna, we have a three-node PS based on the Zigbee standard. The PS used different positioning methods and algorithms to verify the advantages of the proposed BSAA. The PSs using the fingerprinting method archive the best accuracy with the ratio between mean error and area of 0.023.

IV. CONCLUSION

The paper proposes the BSAA using the 4 × 4 Butler matrix with four beams operating at the frequency of 2.45 GHz. The design has several advantages, such as simple structure, high gain, narrow beamwidth in the sweep plane for improving localization accuracy of PSs, suited beamwidth in the orthogonal plane to the sweep one, and a planar structure that is suitable for PC. The antenna array is fabricated and measured with a good agreement between simulation and measurement results. The PS integrated with the antenna using different location methods is implemented to verify the antenna’s advantages of narrow beamwidth in improving the location accuracy. The proposed PS using the fingerprinting method obtains the best ratio between mean error and area of 0.023. In the case of the requirement for a simple configuration, the antenna is suitable for the PS using the triangulation method with an error ratio of 0.033. In the future, the BSAA will continue to optimize the antenna array dimension and the phase shifter to archive a lower PS profile.

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