

Design of a Shared U-Shaped Single Radiator with Multiple Patterns Antenna for UWB Monopulse Systems

Changhyeon Im¹  · Sangwoon Youn²  · Hosung Choo^{1,*} 

Abstract

This paper proposes a single radiator with multiple patterns (SRMP) antenna for miniaturized ultrawideband (UWB) positioning systems. The proposed antenna combines three U-shaped monopole antennas into a single radiator to minimize mounting space. The shared U-shaped monopole antenna is fed by three printed coplanar waveguides with grounds (CPWGs) arranged in a circular configuration. To improve matching characteristics, shorting pins are applied parallel to the inner conductor, maintaining a circular arrangement around the junction between the inner conductor of the CPWGs and the ports. The measured reflection coefficient of Port 1 is calculated to be less than -10 dB from 7.4 GHz to 9 GHz, while the measured mutual coupling is less than -8 dB within the observation range of 7 GHz to 9 GHz. At 8 GHz, the measured boresight gain is 1.4 dBi. Furthermore, the measured radiation patterns are observed to be in good agreement with the simulated results in the *zx*- and *xy*-planes, respectively. In addition, the monopulse ratio in the *xy*-plane has a root-mean-square error of 0.077. These results demonstrate that the proposed SRMP antenna is suitable for use in UWB positioning systems in electronic devices.

Key Words: Monopulse Ratio, Single Radiator Multiple Patterns (SRMP), UWB Positioning Systems.

I. INTRODUCTION

Ultrawideband (UWB) positioning systems are used to obtain location information and control nearby devices [1–6]. In UWB positioning systems, the position of other devices is estimated based on distance and direction information, which are derived using different methods. Typically, distance information is estimated using the time-of-flight (ToF) method, which calculates the distance based on the round-trip time of a signal between a transmitter and a receiver [7–10]. Meanwhile, direction information is obtained from the phase difference of arrival (PDoA) of the signals received by an array antenna [11–13]. However, to obtain both elevation and azimuth direction infor-

mation, at least three antennas operating in the UWB Channel 9 band (7.737–8.236 GHz) are required [14, 15]. This implies that the application of a UWB system within a device requires additional mounting space while also ensuring minimal interference from other communication systems, such as Wi-Fi and Bluetooth. Moreover, the trend of miniaturization of smart devices makes it difficult to integrate systems for various communication systems. To resolve these problems, studies on antenna miniaturization have proposed various methods, such as using half-divided apertures [16], slot structures [17–20], stub structures [21, 22], and parasitic elements [23–25]. Although these methods have resulted in the miniaturization of individual elements, they do not offer any advantage in terms of reducing

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mounting space, owing to the use of three independent radiating elements with array distances. Therefore, research aimed at finding novel approaches to reduce the size of UWB array antenna systems is necessary.

In this paper, we propose a single radiator with multiple patterns (SRMP) antenna for the miniaturization of UWB positioning systems. The proposed antenna combines three U-shaped monopole antennas into a single radiator to minimize mounting space, with each U-shaped radiator designed by combining semicircular and square patches. The radiator achieves wideband characteristics in the UWB Channel 9 band using an exponentially designed curved ground (GND). The shared U-shaped monopole antenna is fed by three printed coplanar waveguides with grounds (CPWGs), arranged in a circular configuration spanning 120° . Furthermore, to improve matching characteristics, shorting pins are applied parallel to the inner conductor, encircling the junction between the inner conductor and the port. CST Studio Suite is employed to design and optimize the proposed antenna [26]. To confirm its feasibility, the SRMP antenna is fabricated, and its performance, including its reflection coefficient, mutual coupling, and radiation pattern, is measured in an anechoic chamber. In addition, the monopulse ratio is derived based on the measured patterns to verify the antenna's direction-finding performance. The findings demonstrate that the proposed SRMP antenna is suitable for use in UWB positioning systems.

II. GEOMETRY AND PERFORMANCE OF THE PROPOSED ANTENNA

Fig. 1 illustrates the geometry of the proposed U-shaped SRMP antenna, designed by overlapping three radiators into one shared radiator to reduce the antenna mounting space. The proposed shared U-shaped monopole antenna comprises a U-shaped radiator and a curved GND, which enable its operation in the UWB Channel 9 band (7.737–8.236 GHz). As depicted in Fig. 1, each U-shaped radiator features a combination of semicircular and square patches. The radiator has a length of l_3 and a width of w_1 , with its lower part bearing a semicircular shape of radius r_1 . Notably, this semicircular shape facilitates the occurrence of various electrical resonances between the ground and the radiator edge, thereby helping achieve broadband characteristics. The radiator is connected to a CPWG transmission line by a printed conductor line p_f of length l_2 and width w_3 . Meanwhile, the CPWGs have a length of l_1 , width of w_2 , and are curved on their sides near the radiator. In this context, the operating frequency range can be calculated using the following equation:

$$C(x) = ae^{bx}.$$

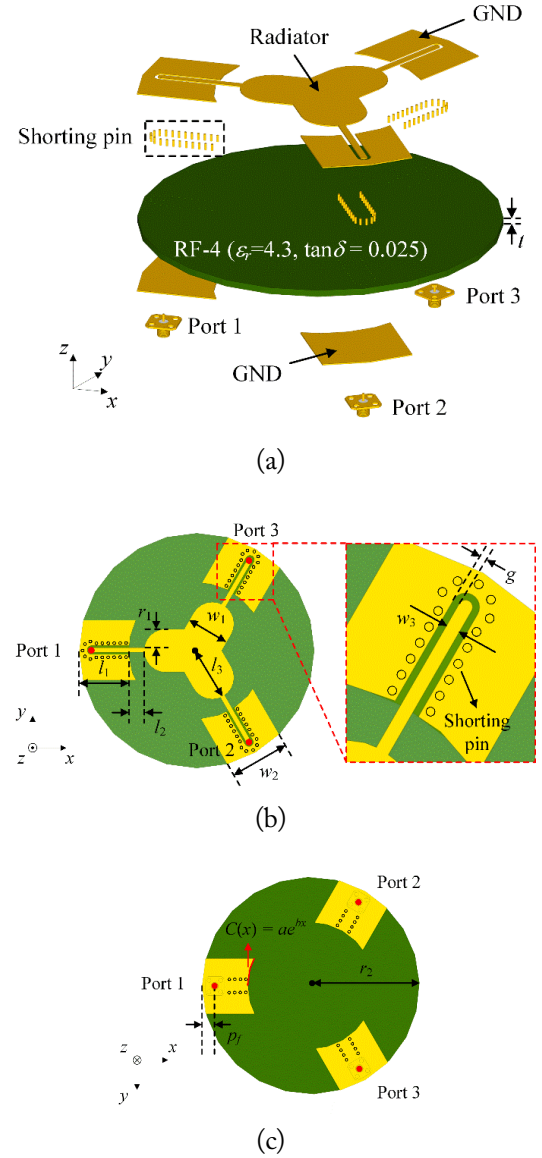


Fig. 1. Geometry of the proposed shared U-shaped single radiator with multiple patterns antenna: (a) Isometric view, (b) top view, and (c) bottom view.

Notably, although both parameters a and b affect curvature, it changes more dramatically when b increases. With regard to the curved GND, it is printed at the same location on both sides of the RF-4 substrate ($\epsilon_r = 4.3$, $\tan \delta = 0.025$), characterized by a radius of r_2 , thickness of t , and width of w_2 . The inner conductor responsible for signal transmission is located inside the upper GND. It is designed to maintain a gap of g with the upper GND. Furthermore, to minimize transmission loss, shorting pins are added to both sides of the inner line so that the upper and lower GNDs of the CPWG are electrically connected. In addition, the shorting pins are arranged in a circular configuration around the feed points (p_f) to reduce losses occurring in the coaxial transmission line structure between the CPWGs and SMA ports.

Each printed monopole antenna exhibited wideband characteristics pertaining to the UWB Channel 9 band. Fig. 1 also shows that the three antennas, positioned in a circular configuration at 120° intervals, share U-shaped radiators. Notably, a circular arrangement was chosen to maintain symmetric geometry and ensure minimum mutual interference between feed ports. The proposed antenna was designed and optimized using CST Studio Suite. The optimum design parameters are listed in Table 1.

Fig. 2 presents photographs of the fabricated antenna and the measurement setup. Fig. 2(a) and 2(b) illustrate the top and bottom views of the antenna, respectively. As is evident from the images, the proposed antenna is directly fed by three SMA connectors. To verify its feasibility, the fabricated antenna was measured in an anechoic chamber, as shown in Fig. 2(c). Fig. 3 presents the measured and simulated S -parameters, revealing that the reflection coefficients (S_{11}) of Port 1 are less than -10 dB from 7.4 GHz to 9 GHz (fractional bandwidth = 19.5% at 8.2 GHz) in the measurement results and from 7.5 GHz to 8.3 GHz (fractional bandwidth = 10.1% at 7.9 GHz) in the simulation results. Furthermore, the mutual coupling (S_{21}) estimated by both the measurement and simulation is less than -8 dB in the frequency range of 7–9 GHz. These observations imply that the proposed antenna is capable of operating well in the UWB Channel 9 band. Fig. 4 shows the measured and simulated 2D radiation patterns of the proposed antenna at 8 GHz. Fig. 4(a) and 4(b) illustrate the 2D radiation patterns in the zx - and zy -planes for Port 1. Notably, the measured and simulated boresight gains were calculated to be 1.4 dBi and 1.2 dBi, respectively. Fig. 4(c), 4(d), and 4(e) show the 2D radiation patterns in the xy -plane at 8 GHz for Ports 1, 2, and 3, respectively. It is evident that the measured radiation patterns are in good agreement with the simulated results.

III. ANALYSIS FOR PERFORMANCE OPTIMIZATION OF THE PROPOSED ANTENNA

Fig. 5 presents a comparison of the bandwidth with design parameters a and b . Fig. 5(a) illustrates the curvature of the

Table 1. Optimized dimensions of the 1×4 array

Parameter	Value	Parameter	Value
l_1	10.3 mm	r_1	3 mm
l_2	1.2 mm	r_2	21.1 mm
l_3	9.6 mm	g	0.2 mm
w_1	7.28 mm	p_f	2.5 mm
w_2	13 mm	a	0.1
w_3	1.28 mm	b	0.5
t	0.8 mm	—	—

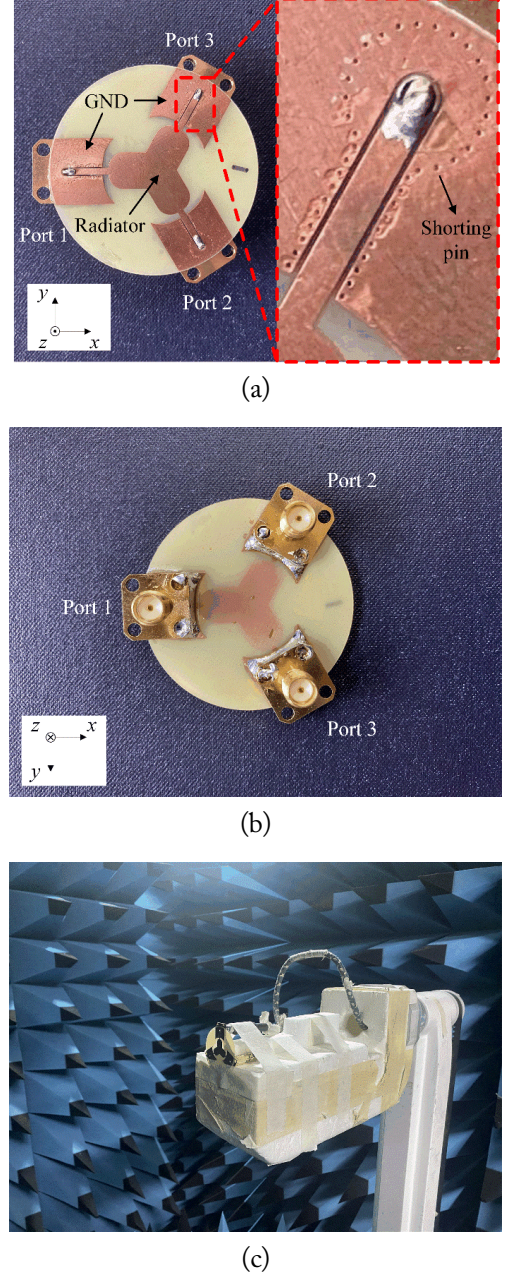


Fig. 2. Photographs of the fabricated antenna and the measurement setup: (a) top view, (b) bottom view, and (c) measurement setup.

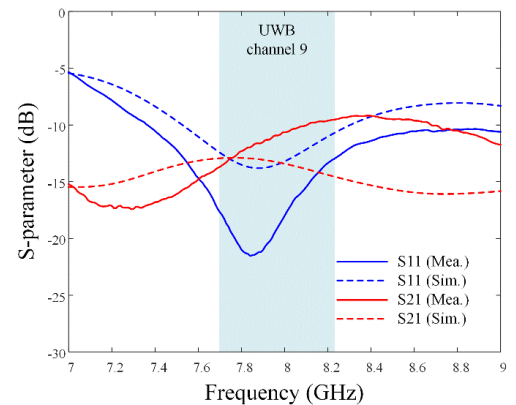


Fig. 3. Measured and simulated S -parameters of the proposed antenna.

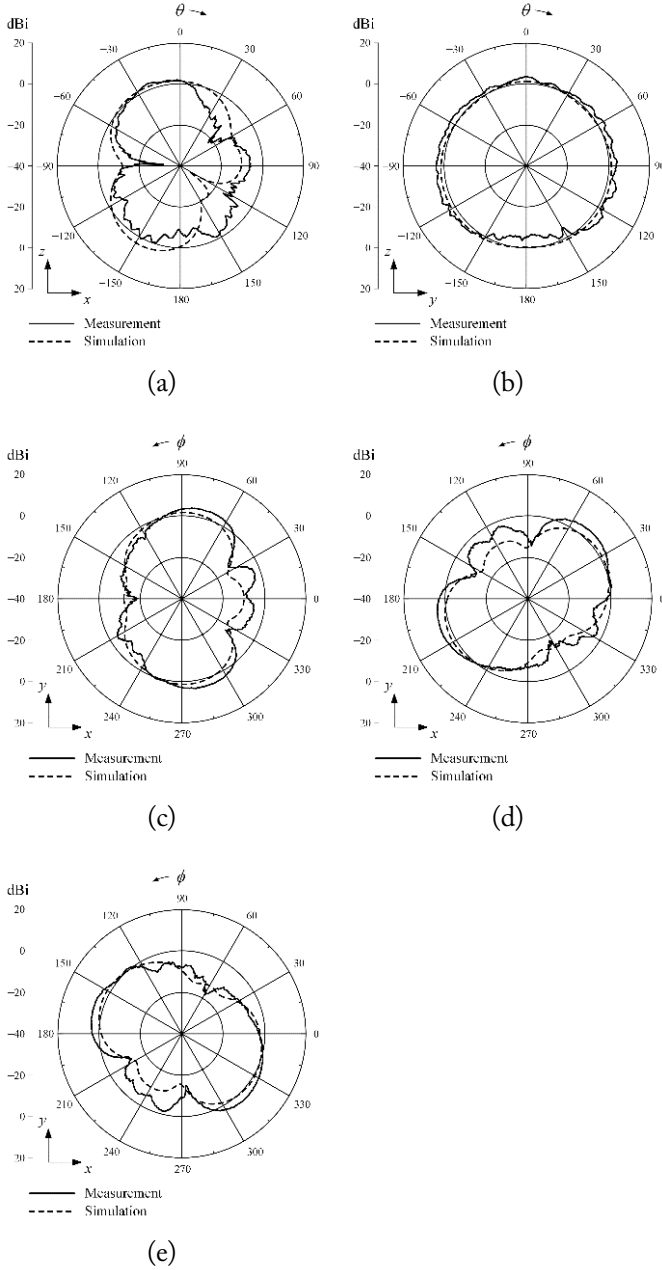


Fig. 4. Measured and simulated 2D radiation patterns of the proposed antenna at 8 GHz: (a) zx-plane (Port 1), (b) zy-plane (Port 1), (c) xy-plane (Port 1), (d) xy-plane (Port 2), and (e) xy-plane (Port 3).

GND of the CPWG with regard to different values of a and b . It is observed that as the value of a increases, the starting point of the GND curve moves closer to the radiator. Meanwhile, as the value of b increases, the slope increases, following a steep trajectory. Fig. 5(b) shows that the bandwidth gradually decreases as a and b increase.

In this context, it must be noted that while achieving a wide bandwidth is important for UWB Channel 9 applications, the operating frequency range should also cover 7.737 GHz to 8.236 GHz. To verify whether this requirement was satisfied,

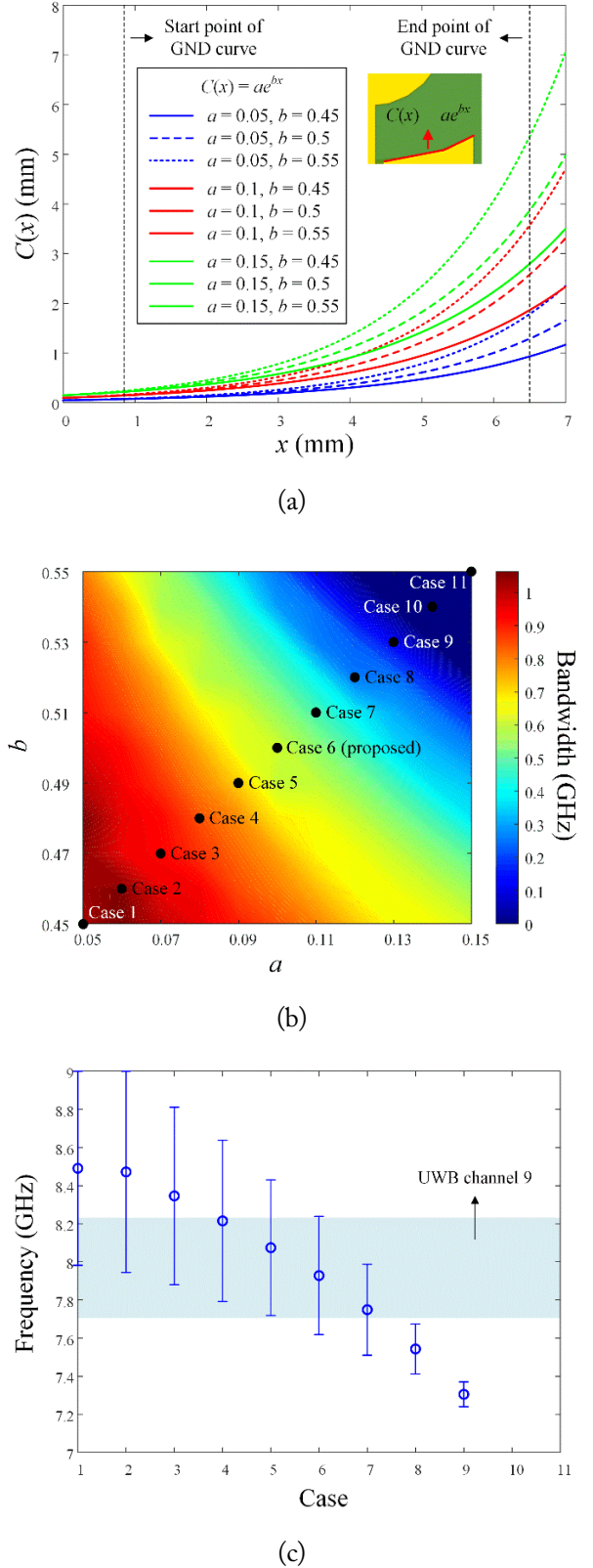


Fig. 5. Comparison of bandwidths based on a and b : (a) curvature, (b) bandwidth, and (c) bandwidth by case.

11 different cases pertaining to different combinations of parameters a and b are considered, and the operating frequency range of each case was calculated. The results are presented in

Fig. 5(c), revealing that Case 6 ($a = 0.1$, $b = 0.5$), operating from 7.62 GHz to 8.24 GHz, satisfies UWB Channel 9.

Fig. 6 compares the reflection coefficients with regard to p_f . It is observed that as the location of the feed point moves away from the edge of the antenna, the center frequency increases, the reflection coefficient deteriorates, and the bandwidth decreases. Based on these results, the optimal reflection coefficient within the UWB Channel 9 band that remains below -10 dB ranges from 7.62 GHz to 8.24 GHz, achieved when $p_f = 2.5$ mm. Fig. 7 presents a comparison of the reflection coefficients based on l_3 of the U-shaped radiator. As l_3 increases, the reflection coefficient improves and the bandwidth increases. However, the physical size of the antenna increases as well. Therefore, considering both the reflection coefficient and physical size, the optimal value of l_3 was chosen as 9.6 mm.

IV. MONOPULSE DOA ESTIMATION

To verify the UWB positioning performance of the proposed antenna, the amplitude comparison monopulse method was im-

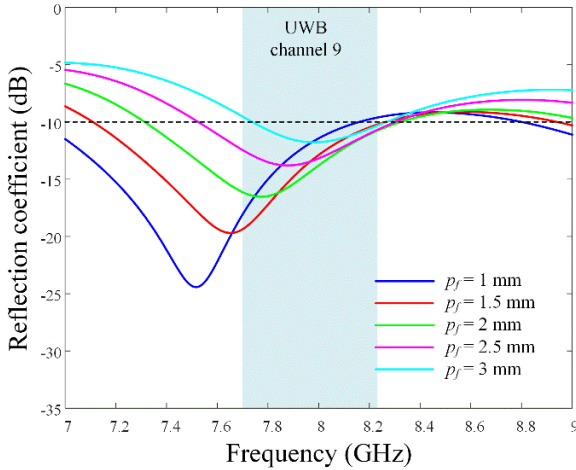


Fig. 6. Comparison of reflection coefficients with p_f .

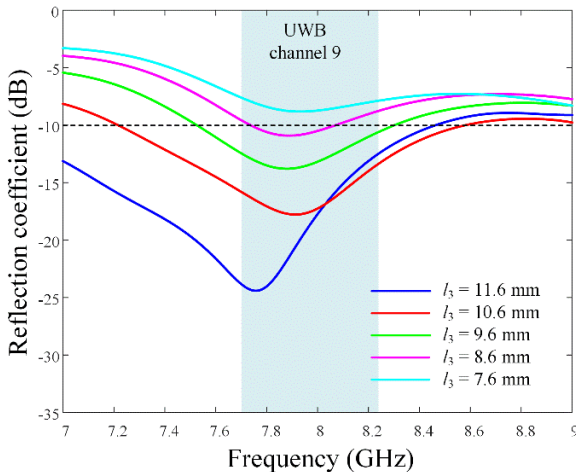


Fig. 7. Comparison of reflection coefficients with l_3 .

plemented. Notably, in UWB positioning systems, the PDoA method is generally used to estimate the incident angle of a signal from the transmitter. However, this method requires multiple radiators and sufficient mounting space for the array antenna. Moreover, the accuracy of the phase information it provides is sensitive owing to the wide bandwidth of more than 500 MHz at the center frequency of 8 GHz. Therefore, the amplitude comparison monopulse method, which is based only on the amplitude of the received signal, was employed for the proposed antenna. The monopulse ratio, which can be derived from the DoA estimation results, was calculated using the following equation:

$$\text{Monopulse ratio} = \frac{\text{Diff}(\phi)}{\text{Sum}(\phi)}.$$

Here, $\text{Diff}(\phi)$ refers to the difference between the patterns of two different radiators, and $\text{Sum}(\phi)$ denotes their summation. In the conventional calculation method for the monopulse ratio, the 2D DoA estimation results are derived from the zx -plane and zy -plane. However, in the case of the proposed antenna, the monopulse ratio was calculated in the xy -plane for the antenna's three ports. Fig. 8 shows the measured (solid line) and simulated (dashed line) summation and difference patterns of the proposed antenna in the xy -plane, confirming that the measurements and simulations of both patterns are symmetrical around 0° . Fig. 9 presents the measured and simulated monopulse ratios in the direction ranging from -20° to 20° . The solid and dashed lines indicate the measurement and simulation results for the monopulse ratio, respectively. Furthermore, to evaluate the direction-finding performance of the antenna, the root mean square error (RMSE) was calculated. An RMSE of 0.077 was obtained, indicating a very low error level.

Table 2 presents a comparison of the proposed antenna with those reported in previous studies. The antenna reported in [6] used a single radiator to achieve miniaturization. However, it

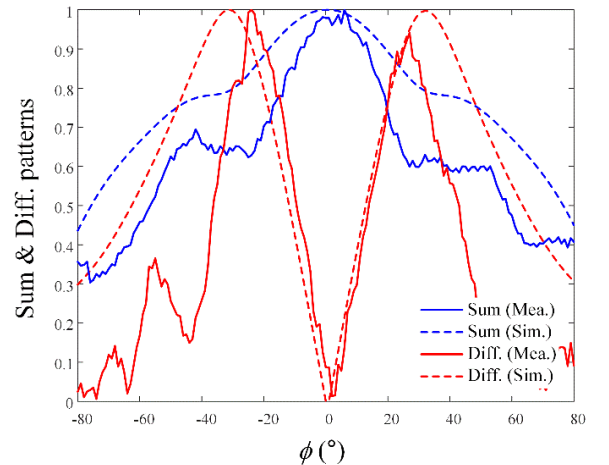


Fig. 8. Measured and simulated summation and difference patterns of the proposed antenna.

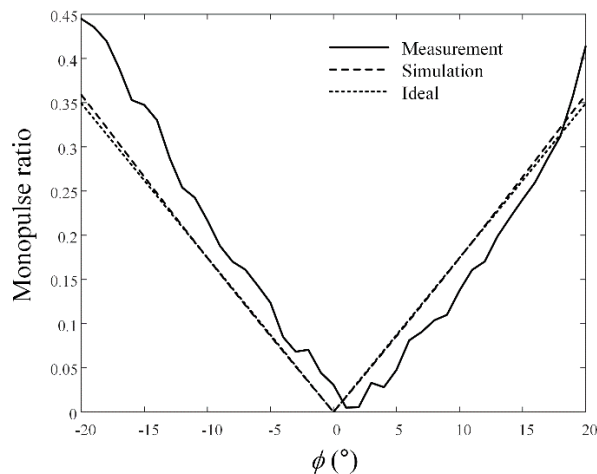


Fig. 9. Measured and simulated monopulse ratios of the proposed antenna.

achieved a mutual coupling of -8.8 dB within the operating band, which is 1.1 dB less than that achieved by the proposed antenna (-9.94 dB). Furthermore, the antennas proposed in previous studies improved their mutual coupling performance by employing multiple independent radiators [27–29], which resulted in large aperture sizes and thicknesses that made them unsuitable for integration into compact mobile devices. In contrast, by adopting a single radiator, the proposed antenna achieves both miniaturization and reduced mutual coupling, making it suitable for use in direction-finding systems for compact mobile devices.

V. CONCLUSION

In this paper, we propose an SRMP antenna for miniaturizing UWB positioning systems that features a shared U-shaped single radiator for minimizing mounting space. The radiator is fed by three printed CPWGs arranged in a circular configuration spanning 120° . Furthermore, to improve matching characteristics, shorting pins were applied parallel to the inner conduc-

tor, encircling the junction between the inner conductor of the CPWGs and ports. The measured reflection coefficient of Port 1 was calculated to be less than -10 dB from 7.4 GHz to 9 GHz, while the measured mutual coupling was less than -8 dB within the observation range of 7 – 9 GHz. At 8 GHz, the measured boresight gain was 1.4 dBi, with the measured radiation patterns in good agreement with the simulated results in the zx - and xy -planes, respectively. Furthermore, the monopulse ratio in the xy -plane, calculated based on three ports, resulted in an RMSE of 0.077 . These results demonstrate that the proposed SRMP antenna is suitable for use in UWB positioning systems in electronic devices.

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Table 2. Comparison between the proposed antenna and antennas reported in previous studies

	This work	[6]	[27]	[28]	[29]
Antenna type	SRMP (monopole)	SRMP (patch)	Patch	Horn	Yagi
Number of radiators	1	1	16	8	4
Mutual coupling (dB)	-9.94	-8.8	-32	-8	-10
Operating freq. (GHz)	7.737 – 8.236	7.737 – 8.236	5.05 – 6.675	1.5 – 5.5	9.4 – 10.05
Boresight gain (dBi)	1.4 (@ 8 GHz, single ant.)	3.4 (@ 8 GHz, single ant.)	18.4 (@ 6 GHz, 4×4 array)	—	9.46 (@ 10 GHz, single ant.)
Aperture size (λ)	1.13×1.13 (@ 8 GHz)	0.53×0.53 (@ 8 GHz)	4.2×4.2 (@ 6 GHz)	0.7×0.7 (@ 1.5 GHz)	3.3×3.3 (@ 10 GHz)
Antenna thickness (λ)	0.02 (@ 8 GHz)	0.04 (@ 8 GHz)	0.13 (@ 6 GHz)	0.275 (@ 1.5 GHz)	0.03 (@ 10 GHz)

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