

Article



# Analysis of Beamforming Antenna for Practical Indoor Location-Tracking Application

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Abstract: The single antenna used in conventional ultra-wideband radar has difficulty tracking targets over a wide range because of a relatively narrow beamwidth. Herein, we propose a beamforming antenna that can track targets over a wide range by electronically controlling the main beam of the antenna. The proposed beamforming antenna was fabricated by connecting a 1 × 4 linear array antenna and a 4 × 4 Butler matrix. The Butler matrix was fabricated in a laminated substrate using two TRF-45 substrates. Furthermore, the input Ports 1–4 generate a phase difference at regular intervals in each output port, and the output phase is fed to the array antenna. The proposed tapered-slot antenna was fabricated on a Taconic TLY substrate, and the impedance bandwidth of the antenna was achieved within a wide bandwidth of 4.32 GHz by satisfying a VSWR (Voltage Standing Wave Ratio)  $\leq$ 2 within the 1.45–5.78 GHz band. Furthermore, the fabricated antenna has directional radiation patterns, which was found to be a suitable characsteristic for location tracking in a certain direction. Finally, the beamforming antenna has four beamforming angles, and to verify the performance for an indoor location tracking application of impulse-radio ultra-wideband radar, it was connected to an NVA-R661 module.

**Keywords:** beamforming antenna; Butler matrix; tapered slot antenna; indoor location tracking; IR-UWB radar

# 1. Introduction

The field of indoor location tracking has recently been applied to various fields, such as military, medical, and civilian areas. Among them, an IR-UWB (Impulse Radio Ultra-Wideband) radar system is a typical example of an indoor location tracking system and makes precise location tracking possible [1].

The antenna used in an IR-UWB radar system must have a wide bandwidth to transmit and receive the impulse signals of nano-second units in a specific direction, as well as high gain and directional radiation patterns to track the location of an object. Conventional IR-UWB antennas have been studied for various uses, such as in Vivaldi antennas [2,3], patch antennas [4], Yagi-type antennas [5,6], and tapered-slot antennas (TSA) [7,8]. These antennas have difficulty tracking objects that are located over a wide area owing to the relatively narrow beamwidth. Furthermore, the individual studies on antennas and their applications in conventional indoor location tracking have not considered the needs of other antenna types.

In this paper, an indoor location-tracking technique based a beamforming antenna developed through a linkage study is proposed.

The proposed beamforming antenna was fabricated by combining beamforming networks that generate a constant phase with a tapered-slot antenna array. The structure of the beamforming antenna requires a beamforming network ( $N \times N$  Butler matrix) capable of providing different constant phases, and an N-array antenna to radiate toward the desired direction [9,10]. The proposed technology was

implemented using a Butler matrix, which is easy to manufacture at low cost. The Butler matrix consists of  $3\text{-}dB/90^\circ$  slot-directional hybrid couplers and  $45^\circ$  phase shifters. When the input and output ports of the Butler matrix increase, the controlled phase beam increases; however, the circuit size also increases, and the design becomes complicated. Therefore, we propose a  $4 \times 4$  Butler matrix with four input and four output ports, where the output phase is fed into the input ports of the linear array antenna. Finally, the proposed beamforming antenna verifies the applicability of indoor location tracking by connecting an NVA-R661 module for a conventional IR-UWB radar.

The remainder of this paper is organized as follows. In Section 2, the fabrication of the proposed beamforming antenna for indoor location tracking is described and analyzed. In Section 3, to verify the performance of indoor location tracking, the fabricated beamforming antenna is connected to the NVA-R661 module for a IR-UWB radar. In Section 4, some concluding remarks are provided.

#### 2. Antenna Design and Analysis

The proposed beamforming antenna for an indoor wireless positioning system is shown in Figure 1. The proposed beamforming antenna was designed by connecting a  $1 \times 4$  array antenna and a  $4 \times 4$  Butler matrix. When configuring the arrays, the distance between each antenna is an extremely important parameter that determines the direction and gain of the main beam. Grating lobes are generated when the distance between each antenna is larger than the wavelength. In contrast, if the distance between each antenna is small, the side lobe level increases owing to the interference between antennas. Therefore, the distance d of the array antenna must satisfy the condition  $\lambda/2 < d < \lambda$ , and a distance d of 30 mm was chosen.



**Figure 1.** Configuration of the proposed beamforming antenna for indoor wireless positioning: (a) geometry and (b) photograph of antenna.

## 2.1. Design and Measurement of Tapered Slot Antenna (TSA)

The configuration of the proposed tapered slot antenna is shown in Figure 2. As Figure 2 indicates, the radiation element is placed on the top layer of the proposed TSA, whereas the transition feed is placed on the bottom layer. The directivity and beamwidth of the proposed TSA can be expressed as (1) and (2).

Directivity 
$$[dB] = 10 \log \left( 10 \frac{L_T}{\lambda_0} \right)$$
,  
Beamwidth  $[^\circ] = \frac{55}{\sqrt{L_T / \lambda_0}}$ , (1)  
Directivity  $[dB] = 10 \log \left( 4 \frac{L_T}{\lambda_0} \right)$ ,  
Beamwidth  $[^\circ] = \frac{77}{\sqrt{L_T / \lambda_0}}$ , (2)

where  $\lambda_0$  is the wavelength for the center frequency of the proposed TSA, and  $L_T$  is the aperture length [11]. The proposed tapered slot antenna was designed using HFSS ver. 12 (Ansys Co., Canonsburg, PA, USA), and the design parameters were determined through a repeated analysis. Furthermore, the antenna was fabricated through an etching process using a Taconic TLY substrate, which has a relative permittivity of 2.2, loss tangent of 0.0009, and thickness of 1.52 mm.



(b)

Figure 2. Configuration of the proposed tapered slot antenna: (a) geometry and (b) photograph of antenna.

The design parameters of the proposed tapered slot antenna were as follows:  $L_S = 140 \text{ mm}$ ,  $W_S = 90 \text{ mm}$ ,  $L_T = 96.8 \text{ mm}$ ,  $L_{T_1} = 23 \text{ mm}$ ,  $W_T = 80 \text{ mm}$ ,  $L_m = 45 \text{ mm}$ ,  $L_{m_1} = 15 \text{ mm}$ , and  $W_m = 5 \text{ mm}$ .

The impedance bandwidth and gain results of the fabricated tapered slot antenna are shown in Figure 3.

The simulation results in Figure 3 show that the impedance bandwidth of the fabricated tapered slot antenna achieved a wide bandwidth of 4.29 GHz, which was satisfied by VSWR  $\leq$  2 within the 1.45–5.74 GHz band. The simulation gain results are 6.7, 8.36, and 8.97 dBi at 3–5 GHz, respectively. The measurement results show that impedance bandwidth of the fabricated TSA achieves a wide bandwidth of 4.32 GHz by satisfying VSWR  $\leq$  2 within the 1.46–5.78 GHz band. The measurement gain results are 6.17, 8.19, and 9.18 dBi at 3–5 GHz, respectively.



Figure 3. Results of the impedance bandwidth.

The radiation pattern results of the fabricated tapered slot antenna were analyzed in the E-plane (y-z) and H-plane (x-z), as shown in Figure 4.



Figure 4. Simulation and measurement results of the radiation pattern: (a) 3, (b) 4, and (c) 5 GHz.

The results in Figure 4 indicate that the E-plane and H-plane radiation patterns of the proposed TSA exhibit the directivity of an end-fire, which increases the sensitivity for a certain direction. The 3 dB beamwidth simulation results of the E-plane and H-plane were 70.45° and 117.00° at 3 GHz, 58.03° and 96.38° at 4 GHz, and 36.48° and 72.25° at 5 GHz. Furthermore, the measured results show 72° and 109° at 3 GHz, 40° and 84° at 4 GHz, and 29° and 60° at 5 GHz, respectively.

Comparisons of the simulation and measurement results of the fabricated TSA are shown in Table 1.

Parameters	Simulation Results			Measurement Results			
Impedance bandwidth	1.45–5.74 GHz			1.46–5.78 GHz			
Antenna Beamwidth	3 GHz	E H	70° 117°	3 GHz	E H	72° 109°	
	4 GHz	E H	58° 96°	4 GHz	E H	$40^{\circ}$ $84^{\circ}$	
	5 GHz	E H	36° 72°	5 GHz	E H	29° 60°	
Antenna gain	3 GHz 4 GHz 5 GHz	6.70 dBi 8.36 dBi 8.97 dBi		3 GHz 4 GHz 5 GHz	6.17 dBi 8.19 dBi 9.18 dBi		

Table 1. Comparisons of simulation and measurement results.

As shown in Table 1, the simulation and measurement results of the fabricated TSA show a proper agreement, although small errors were observed in certain areas. The reason for this is presumably due to errors during the fabrication process and a loss between the antenna and a connector.

#### 2.2. Design and Measurement of Butler Matrix

The proposed  $4 \times 4$  Butler matrix consists of 3-dB/90° slot-directional hybrid couplers and  $45^{\circ}$  phase shifters, and has four input/output ports. The proposed  $4 \times 4$  Butler matrix is shown in Figure 5. The 3-dB/90° slot-directional hybrid coupler and  $45^{\circ}$  phase shifter are operated through the coupling slot between the coupling patches located at the top and bottom layers. The proposed 3-dB/90° slot-directional hybrid couplers and  $45^{\circ}$  phase shifter can be expressed as (3).

$$L_p(L_g) = \frac{\lambda_c}{4} \left[ 1 - \left( \frac{\pi (W_p + W_g)}{4\lambda_c} \right)^2 \right]^{-1}, t$$
(3)

where the length  $L_p$  ( $L_g$ ) of the coupling patch and coupling slot can be calculated from the effective wavelength  $\lambda_c$  at the center frequency of the coupler, and from the shifter and width  $W_p$ ,  $W_G$  of the coupler patch and coupler slot [9]. The proposed 3-dB/90° slot-directional hybrid coupler and 45° phase shifter were designed using HFSS ver. 12, and the design parameters were determined through a repeated analysis.

As shown in Figure 5b, the proposed 3-dB/90° slot-directional hybrid couplers were designed as a laminated substrate using two TRF-45 substrates, which have a relative permittivity of 4.5, a loss tangent of 0.0035, and a thickness of 0.61 mm. The proposed 3-dB/90° slot-directional hybrid coupler consists of four ports, namely an input port, a direct port, a coupled port, and an isolated port, and is placed on the two signal lines on the top and bottom layers. The ground plane of the intermediate layer is inserted into a rectangular slot, and its structure is mutually coupled. The design parameters of the 3-dB/90° slot-directional hybrid coupler are as follows:  $L_S = 30 \text{ mm}$ ,  $W_S = 12.8 \text{ mm}$ ,  $L_p = 10 \text{ mm}$ ,  $W_p = 5 \text{ mm}$ ,  $W_{p1} = 3 \text{ mm}$ ,  $L_g = 10 \text{ mm}$ ,  $W_g = 6.4$ , and  $W_m = 1.2 \text{ mm}$ .

For the proposed 45° phase shifter shown in Figure 5c, the signal lines were placed on the top and bottom layers. The ground plane of the intermediate layer was inserted into a rectangular slot, and its structure was mutually coupled. The design parameters of the 45° phase shifter are as follows:  $L_S = 43.6 \text{ mm}$ ,  $W_S = 25 \text{ mm}$ ,  $L_p = 9 \text{ mm}$ ,  $W_p = 5 \text{ mm}$ ,  $W_{p1} = 3.2 \text{ mm}$ ,  $L_g = 9 \text{ mm}$ ,  $W_g = 6.6 \text{ mm}$ ,  $L_m = 13.1 \text{ mm}$ ,  $L_{m1} = 10.4$ , and  $W_m = 1.2 \text{ mm}$ .

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The S-parameters of the proposed 3-dB/90° slot-directional hybrid coupler were analyzed in terms of the return loss S11, isolation S41, and insertion losses S21, S31, which are shown in Figure 6.



**Figure 5.** Configuration of the Butler matrix: (a) structure of the Butler matrix, (b) structure of the  $3-dB/90^{\circ}$  slot-directional hybrid coupler, and (c) structure of  $45^{\circ}$  phase shifter.



Figure 6. S-parameter simulation analysis of the proposed coupler.

The simulation results in Figure 6 show that the return loss  $S_{11}$  and isolation loss  $S_{41}$  achieved good results of lower than -20 dB within the 3–5 GHz band. In addition, the insertion losses  $S_{21}$  and  $S_{31}$  were 3 dB within the 3–5 GHz band; overall, the error observed was  $\pm 0.4$  dB.

The results of the phase and phase difference simulation analyses of the proposed 3-dB/90° slot-directional hybrid coupler are shown in Figure 7.



Figure 7. Phase and phase difference simulation analysis of the proposed coupler.

The simulation results in Figure 7 show that the  $S_{31}$  and  $S_{21}$  phases of the proposed 3-dB/90° slot-directional hybrid coupler are 227° and 138° at 3 GHz, 161° and 72° at 4 GHz, and 95° and 5° at 5 GHz. The simulation analysis of the phase difference shows an error of ±2° at 90°.

The S-parameter simulation results of the proposed  $45^{\circ}$  phase shifter were analyzed in terms of the return loss S<sub>11</sub> and insertion loss S<sub>21</sub>, which are indicated in Figure 8.

The simulation results in Figure 8 show that the return loss  $S_{11}$  achieved good results of less than -20 dB within the 3–5 GHz band. The insertion loss  $S_{21}$  was between -0.4 and -0.7 dB within the 3–5 GHz band.

The results of the phase and phase difference simulation analyses of the proposed 45° phase shifter are shown in Figure 9.

The simulation results in Figure 9 indicate that the S<sub>21</sub> and S<sub>31</sub> phases of the proposed 45° phase shifter are 171° and 125° at 3 GHz, 91° and 46° at 4 GHz, and 12° and -32° at 5 GHz. The phase difference simulation analysis showed an error of  $\pm 2°$  at 45°.

Therefore, the return loss results of the proposed coupler and shifter are extremely low, with good insertion loss and isolation characteristics. Furthermore, the phase difference of the coupler and

shifter was approximately 90° and 45° within the proposed bandwidth, respectively. The proposed Butler matrix is realized by combining the designed four couplers and two shifters, and the design parameters of the Butler matrix are the same as those of the couplers and shifters.



Figure 8. S-parameter simulation analysis of the proposed shifter.



Figure 9. Phase and phase difference simulation analysis of the proposed shifter.

The S-parameter simulation results of the Butler matrix for input Ports 1 and 2 are shown in Figures 10 and 11, respectively.



Figure 10. Simulation analysis of S-parameters for input Port 1.

The simulation results in Figure 10 show that the return loss  $S_{11}$  and isolation losses  $S_{21}$ ,  $S_{31}$ , and  $S_{41}$  are less than -20 dB within the proposed bandwidth. The insertion losses  $S_{51}$ ,  $S_{61}$ ,  $S_{71}$ , and  $S_{81}$  are low at approximately 6–6.7 dB within the proposed bandwidth.

The simulation results in Figure 11 show that the return loss  $S_{22}$  and isolation losses  $S_{12}$ ,  $S_{32}$ , and  $S_{42}$  are less than -20 dB within the proposed bandwidth. The insertion losses  $S_{52}$ ,  $S_{62}$ ,  $S_{72}$ , and  $S_{82}$  are low at approximately 6–7.4 dB within the proposed bandwidth.



Figure 11. Simulation analysis of S-parameters for input Port 2.

The results of the phase and phase difference simulation analyses for Ports 1 and 2 of the proposed Butler matrix are shown in Figures 12–15, and are listed in Table 2.



Figure 12. Simulation analysis of phase for input Port 1.

**Table 2.** Simulation results of phase difference for  $4 \times 4$  Butler matrix.

	Output Port	Phase [Deg.]			Phase Difference [Deg.]			
Input Port		Port 5	Port 6	Port 7	Port 8	$P_{5x}-P_{6x}$	$P_{6x}-P_{7x}$	$P_{7x}-P_{8x}$
	3 GHz	17	59	103	148	-42	-44	-45
Port 1	4 GHz	139	-177	-133	-88	-44	-44	-45
	5 GHz	-100	-56	-10	34	-44	-46	-44
	3 GHz	103	-29	-167	58	132	138	135
Port 2	4 GHz	-133	92	-44	-178	135	136	134
	5 GHz	-10	-147	76	-56	135	138	132



Figure 13. Simulation analysis of phase difference for input Port 1.



Figure 14. Simulation analysis of phase for input Port 2.



Figure 15. Simulation analysis of phase difference for input Port 2.

The simulation results for Port 1 in Table 2 show that, within the 3 GHz band, the phase is  $17^{\circ}$  and  $59^{\circ}$  for P<sub>51</sub> and P<sub>61</sub>,  $59^{\circ}$  and  $103^{\circ}$  for S<sub>61</sub> and S<sub>71</sub>, and  $103^{\circ}$  and  $148^{\circ}$  for S<sub>71</sub> and S<sub>81</sub>, respectively. The phase for Port 2 is  $103^{\circ}$  and  $-29^{\circ}$  for P<sub>52</sub> and P<sub>62</sub>,  $-29^{\circ}$  and  $-167^{\circ}$  for S<sub>62</sub> and S<sub>72</sub>, and  $-167^{\circ}$  and  $58^{\circ}$  for S<sub>72</sub> and S<sub>82</sub>, respectively. Therefore, the simulation results of the phase difference for Ports 1 and 2 are  $-45^{\circ} \pm 3^{\circ}$  and  $135 \pm 2^{\circ}$  within the 3 GHz band. Similar results are shown at the other frequency bands (4 and 5 GHz).

The S-parameter measurement results of the Butler matrix for input Ports 1 and 2 are shown in Figures 16 and 17.



Figure 16. Measurement analysis of S-parameters for input Port 1.



Figure 17. Measurement analysis of S-parameters for input Port 2.

The measurement results in Figure 16, show that the return loss  $S_{11}$  and isolation losses  $S_{21}$ ,  $S_{31}$ , and  $S_{41}$  were less than -15 dB within the 3–5 GHz band. The insertion losses  $S_{51}$ ,  $S_{61}$ ,  $S_{71}$ , and  $S_{81}$  showed a low insertion loss of approximately 6.2–6.8 dB within the proposed bandwidth.

The measurement results in Figure 17 show that the return loss  $S_{22}$  and isolation losses  $S_{12}$ ,  $S_{32}$ , and  $S_{42}$  are less than -10 dB within the 3–5 GHz band. In addition, the insertion losses  $S_{52}$ ,  $S_{62}$ ,  $S_{72}$ , and  $S_{82}$  show a low insertion loss of approximately 6.1–6.7 dB within the proposed bandwidth.

The results of the phase and phase difference measurement analysis for Ports 1 and 2 of the proposed Butler matrix are shown in Figures 18–21, and are listed in Table 3.

The measurement results for Port 1 in Table 3 show that within the 3 GHz band, the phase is  $-68^{\circ}$  and  $-25^{\circ}$  for P<sub>51</sub> and P<sub>61</sub>,  $-25^{\circ}$  and 20° for S<sub>61</sub> and S<sub>71</sub>, and 20° and 62° for S<sub>71</sub> and S<sub>81</sub>. The phase of Port 2 is 19° and  $-116^{\circ}$  for P<sub>52</sub> and P<sub>62</sub>,  $-116^{\circ}$  and 109° for S<sub>62</sub> and S<sub>72</sub>, and 109° and  $-30^{\circ}$  for S<sub>72</sub> and S<sub>82</sub>. Therefore, the measurement results of the phase difference for Ports 1 and 2 are  $-45^{\circ} \pm 3^{\circ}$  and  $135 \pm 4^{\circ}$  at 3 GHz. Similar results are shown at the other frequency bands (4 and 5 GHz). The simulation and measurement analysis results of the fabricated Butler matrix in Tables 2 and 3 show similar results at 3, 4, and 5 GHz. In addition, Ports 3 and 4 are symmetrical with respect to Ports 1 and 2, and output opposite polarities of  $-135^{\circ}$  and  $45^{\circ}$ , respectively.



Figure 18. Measurement analysis of phase for input Port 1.



Figure 19. Measurement analysis of phase difference for input Port 1.



Figure 20. Measurement analysis of phase for input Port 2.

In order to observe the characteristic for the time delay of the proposed  $4 \times 4$  Butler matrix in a wide bandwidth, the group delay is analyzed and is shown in Figure 22.

In the group delay analysis in Figure 22, the results of output ports for input Ports 1 and 2 has a constant time delay characteristic at about 60 nano second.



Figure 21. Measurement analysis of phase difference for input Port 2.

Therefore, the output phase from the Butler matrix is fed into the input port of the  $1 \times 4$  array antenna. A photograph of the fabricated Butler matrix is shown in Figure 23.



**Figure 22.** Group delay analysis of the proposed 4 × 4 Butler matrix (**a**) results of output ports for input Port 1, (**b**) results of output ports for input Port 2.

	Output Port	Phase [Deg.]				Phase Difference [Deg.]		
Input Port		Port 5	Port 6	Port 7	Port 8	P <sub>5x</sub> -P <sub>6x</sub>	$P_{6x}-P_{7x}$	$P_{7x}-P_{8x}$
	3 GHz	-68	-25	20	62	-43	-45	-42
Port 1	4 GHz	23	66	116	155	-43	-50	-39
	5 GHz	115	157	-156	-113	-42	-47	-43
	3 GHz	19	-116	109	-30	135	135	139
Port 2	4 GHz	115	-25	-156	58	140	131	146
	5 GHz	-153	63	-62	156	144	125	142

**Table 3.** Measurement results of phase difference for  $4 \times 4$  Butler matrix.



**Figure 23.** Photograph of fabricated  $4 \times 4$  Butler matrix.

The simulation results of the radiation pattern for the proposed beamforming antenna are shown in Figure 24.



**Figure 24.** Simulation results of the fabricated phased array antenna at each frequency: (**a**) 3, (**b**) 4, and (**c**) 5 GHz.

The results in Figure 24 indicate that the simulated beamforming angles at 3 GHz are  $-22^{\circ}$ ,  $+60^{\circ}$ ,  $-62^{\circ}$ , and  $+22^{\circ}$ . At 4 GHz, the simulation results are  $-16^{\circ}$ ,  $+45^{\circ}$ ,  $-50^{\circ}$ , and  $+16^{\circ}$ . At 5 GHz, the simulation results are  $-14^{\circ}$ ,  $+38^{\circ}$ ,  $-38^{\circ}$ , and  $+14^{\circ}$ . The simulation gain results at each beamforming angle are 7.26, 11.06, 11.04, and 6.89 dBi within the 3 GHz band; 10.88, 13.39, 13.27, and 10.73 dBi within the 4 GHz band; and 12.08, 13.63, 13.77, and 12.71 dBi within the 5 GHz band, respectively.

The radiation patterns of the fabricated beamforming antenna were measured using a far-field analysis system in an anechoic chamber room (EMTI Co., Seoul, Korea), as shown in Figure 25.



Figure 25. Measurement configuration of the fabricated beamforming antenna.

When the feed wave was fed to each input port, the terminating resistance was connected to the remaining ports. The results of the radiation pattern analysis of the fabricated beamforming antenna are shown in Figure 26.



**Figure 26.** Measured results of the fabricated phased array antenna at each frequency: (**a**) 3, (**b**) 4, and (**c**) 5 GHz.

The results in Figure 26 show that the measured beamforming angles are  $-21^{\circ}$ ,  $+59^{\circ}$ ,  $-56^{\circ}$ , and  $+23^{\circ}$  within the 3 GHz band;  $-14^{\circ}$ ,  $+46^{\circ}$ ,  $-44^{\circ}$ , and  $+16^{\circ}$  within the 4 GHz band; and  $-13^{\circ}$ ,  $+44^{\circ}$ ,  $-36^{\circ}$ ,

and +17° within the 5 GHz band, respectively. The measurement gain results at each beamforming angle are 7.98, 10.40, 10.04, and 8.01 dBi at 3 GHz; 9.25, 11.41, 10.98, and 9.41 dBi at 4 GHz, and 9.17, 10.05, 9.10, and 10.07 dBi at 5 GHz, respectively.

The proposed beamforming antenna shows similar results within the proposed frequency band. Therefore, the maximum beamforming range of the fabricated antenna is  $115^{\circ}$  (+59° to -56°) within the 3 GHz band, 90° (+46° to -44°) within the 4 GHz band, and 80° (+44 to -36°) within the 5 GHz band.

## 3. Target Tracking Test of Fabricated Beamforming Antenna

This chapter describes a simple experiment conducted to verify the practicability of the fabricated antenna. The configuration of the experiment is shown in Figure 27.



Figure 27. Proposed system: experiment environments (a) Configuration (b) #1 and (c) #2.

As shown in Figure 27, the proposed radar system is connected to the fabricated beamforming antenna and NVA-R661 UWB radar module (Xethru Co., Oslo, Norway) [12]. The proposed radar system has four measurement regions according to the four input ports, and the angle  $\theta$  between each point is 15°.

# Test of Indoor Location Tracking for Beamforming Antenna

The radar and signal processing procedure is shown in Figure 28.



Figure 28. Configuration of the proposed radar system: (a) radar connected to beamforming antenna and NVA-R661 module and (b) signal processing.

As shown in Figure 28, the signal processing procedure consists of clutter reduction, detection, and localization and tracking steps. The raw data detected at each port are signal processed using the NVA-R661 module. The raw data reflected from a single target are given by:

$$R_i = R_{t,i} + R_{c,i} + R_{n,i}, (4)$$

where  $R_i$  is the *i*-th raw data reflected from a single target and consists of the target signal  $R_{t,i}$ , clutter signal  $R_{c,i}$ , and noise  $R_{n,i}$ . In the clutter reduction step, the main purpose is to remove the clutter signal included in the raw data. To remove the clutter signal, the singular value decomposition algorithm is used. The *n* signal reflected comprises matrix *R* with  $R = [R_1, R_2, ..., R_n]^t$ . Matrix *R* is given by:

$$R = R_T + R_C + N \tag{5}$$

Matrix *R* consists of the target signal  $R_T$ , clutter signal  $R_C$ , and noise *N*. To remove the clutter signal in *R*, it is decomposed using  $R = USV^T$ , where *R* is an m × n matrix, and *U* and *V* are the orthogonal matrices of  $m \times m$  and  $n \times n$ . Therefore, *R* is given by:

$$R = \sum_{i=1}^{j} \sigma_i u_i v_i^T \tag{6}$$

where  $u_i$  is the *i*-th singular value of R, and  $\sigma_i$  and  $v_i$  are the *i*-th eigenvectors to the left and right of R. The target  $R_T$  is obtained using R and  $R_C$ .

$$R_T + N = R - R_C \tag{7}$$

During the detection step, the location of the target is determined [13–16]. Finally, during the localization and tracking step, the distance of a target is detected using the time of arrival [17,18].

A single target analysis using the proposed beamforming antenna is shown in Figure 29.

The results in Figure 29 show that at Port 3, a target is detected at 2 m within the regions of P2, P3, and P4. At Port 1, a target is detected at 2 m within the regions of P4, P5, and P6. At Port 4, a target is detected at 2 m within the regions of P6, P7, and P8. At Port 2, a target is detected at 2 m within the regions of P8, P9, and P10. Therefore, the results of the target tracking show that the target is detected at 2 m within the region of P2–P10.





Figure 29. Cont.





**Figure 29.** Measured results of single target using proposed beamforming antenna: (**a**) P2, (**b**) P3, (**c**) P4, (**d**) P4, (**e**) P5, (**f**) P6, (**g**) P6, (**h**) P7, (**i**) P8, (**j**) P8, (**k**) P9, and (**l**) P10.

**Table 4.** Comparisons of the proposed 4 × 4 beamforming antenna and reference antennas.

	Ref. [9]	Ref. [19]	Ref. [20]	This Work
Antenna Type	Beamforming antenna	Single antenna	Single antenna	Beamforming Antenna
Measurement Set-up	-	1D set-up	2D set-up	Set-up for Beamforming

As shown in Table 4. the beamforming antenna in [9] led to a great deal of inspiration for this work, but it somewhat lacks the measurement results. In the case of [18] and [19], it provides an indoor location tracking system in 1 dimension and 2 dimensions coordinate system. In Ref. [19], the indoor

location tracking measurement of 2 dimension coordinate require two radars to operate. The proposed  $4 \times 4$  beamforming antenna has the advantage of measuring the targets located at various angles. Therefore, the fabricated beamforming antenna provides a solution to enable the tracking of targets over a wide range compared with a conventional IR-UWB antenna.

## 4. Conclusions

In this paper, an overview of a beamforming antenna that can track the location of a target over a wide range was described. Conventional IR-UWB antennas have difficultly tracking a target over a wide range because of the relatively narrow beamwidth. To solve this problem, a beamforming antenna that tracks a target over a wide range by electronically controlling the beam of the antenna was proposed.

The beamforming antenna was fabricated by connecting a  $4 \times 4$  Butler matrix and a  $1 \times 4$  array antenna. The feed wave generated in the  $4 \times 4$  Butler matrix is fed into the  $1 \times 4$  array antenna, which controls the four beams.

The fabricated beamforming antenna has beamforming angles of  $-21^{\circ}$ ,  $+59^{\circ}$ ,  $-56^{\circ}$ , and  $+23^{\circ}$  at 3 GHz;  $-14^{\circ}$ ,  $+46^{\circ}$ ,  $-44^{\circ}$ , and  $+16^{\circ}$  at 4 GHz; and  $-13^{\circ}$ ,  $+44^{\circ}$ ,  $-36^{\circ}$ , and  $+17^{\circ}$  at 5 GHz. Therefore, the beamforming angles of the fabricated beamforming antenna have maximum values of  $115^{\circ}$ ,  $90^{\circ}$ , and  $80^{\circ}$  within the 3, 4, and 5 GHz bands, respectively. The results of location tracking show that a target can be detected at 2 m within the regions of P2–P10.

Previously published studies in this regard have not been able to meet the needs of individual antennas and applications. An IR-UWB antenna cannot track a broad range of targets owing to the narrow beamwidth of the directional pattern. In this study, we propose an antenna based on beamforming and verify the possibility of indoor location tracking technology within a wide range by applying a commercialized module. In addition, because the main beam of the antenna is electronically steered, it is possible to detect and track multiple targets at the same time such that they can be utilized in various application technologies. The development of a new indoor location tracking algorithm based on a beam steering system is, therefore, expected.

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